CRREL
# REPORT 88-12

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

(4)



# New England mountain icing climatology



*For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380,* Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

*Cover: Television antenna near the summit of Mt. Mansfield, Vermont, with and without heavy rime icing. One of the recording instruments discussed in this report is attached to the rightmost antenna leg.*

CRREL Report 88-12

August 1988

# New England mountain icing climatology

Charles C. Ryerson

Prepared for
OFFICE OF THE CHIEF OF ENGINEERS

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

# REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188
Exp Date Jun 30, 1986

| | |
|---|---|
| 1a REPORT SECURITY CLASSIFICATION: Unclassified | 1b RESTRICTIVE MARKINGS |
| 2a SECURITY CLASSIFICATION AUTHORITY | 3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited. |
| 2b DECLASSIFICATION/DOWNGRADING SCHEDULE | |
| 4 PERFORMING ORGANIZATION REPORT NUMBER(S): CRREL Report 88-12 | 5 MONITORING ORGANIZATION REPORT NUMBER(S) |
| 6a NAME OF PERFORMING ORGANIZATION: U.S. Army Cold Regions Research and Engineering Laboratory; 6b OFFICE SYMBOL (If applicable): CECRL | 7a NAME OF MONITORING ORGANIZATION: Office of the Chief of Engineers |
| 6c ADDRESS (City, State, and ZIP Code): Hanover, New Hampshire 03755-1290 | 7b ADDRESS (City, State, and ZIP Code): Washington, D.C. 20314-1000 |
| 8a NAME OF FUNDING/SPONSORING ORGANIZATION; 8b OFFICE SYMBOL (If applicable) | 9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER |
| 8c ADDRESS (City, State, and ZIP Code) | 10 SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO.; PROJECT NO. 4A161102AT24; TASK NO. FS; WORK UNIT ACCESSION NO. 005 |

11 TITLE (Include Security Classification)

New England Mountain Icing Climatology

12 PERSONAL AUTHOR(S)

Ryerson, Charles C.

| 13a TYPE OF REPORT | 13b TIME COVERED | 14 DATE OF REPORT (Year, Month, Day) | 15 PAGE COUNT |
|---|---|---|---|
| | FROM ______ TO ______ | August 1988 | 42 |

16 SUPPLEMENTARY NOTATION

| 17 COSATI CODES | | |
|---|---|---|
| FIELD | GROUP | SUB-GROUP |
| | | |
| | | |

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

Antenna icing; Atmospheric icing; Ice detectors; Icing; Mount Mansfield; Mount Washington

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Statistics and weather maps are used to compare the atmospheric icing climatology of two New England mountains: Mount Mansfield in northern Vermont and Mount Washington in New Hampshire. Atmospheric icing, as measured with Rosemount ice detectors, is twice as frequent on Mount Washington, with about 12–20 times greater intensities and 25–50 times more accretion. Periods between icing events average 35–45 hours on the two peaks. Most Mount Mansfield icing events are of low intensity. Plots indicate the return probabilities of ice events by length, intensity and accretion magnitude. Approximately half of all severe icing on the two peaks occurs during and immediately after cold front passages. Icing is most intense when lows are about 450 km to the east of the mountains. High-pressure centers are never closer than about 450 km during intense icing. Prolonged accretion periods occur when coastal and inland storms merge or follow closely.

| | |
|---|---|
| 20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS | 21 ABSTRACT SECURITY CLASSIFICATION: Unclassified |
| 22a NAME OF RESPONSIBLE INDIVIDUAL: Charles C. Ryerson | 22b TELEPHONE (Include Area Code): 603 646 4100; 22c OFFICE SYMBOL: CECRL-RS |

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

## PREFACE

This report was prepared by Dr. Charles C. Ryerson, Research Physical Scientist, Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the Office of the Chief of Engineers under DA Project 4A161102AT24, *Research in Snow, Ice and Frozen Ground*, Task Area FS, Work Unit 005, *Cold Regions Meteorological Processes.*

The author thanks the following individuals and organizations for supporting this research. Walter B. Tucker III and Stephen F. Ackley of the CRREL Snow and Ice Branch provided encouragement and advice. John Govoni and Nathan Mulherin, also of the CRREL Snow and Ice Branch, facilitated data acquisition and analysis and critiqued early manuscript drafts. Brian Marshall and Ronald Whitcomb of Vermont Educational Television assisted with Mount Mansfield ice data acquisition. John Howe and Kenneth Rancourt of the Mount Washington Observatory appraised analyses and helped with literature and Rosemount data acquisition and transcription. Kathy Jones of the CRREL Snow and Ice Branch and Wayne Hershey of Rosemount, Inc., provided invaluable assistance with the ice detector calibration procedure.

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products.

## CONTENTS



## ILLUSTRATIONS

## TABLES

# New England Mountain Icing Climatology

CHARLES C. RYERSON

## INTRODUCTION

Weather causing atmospheric icing on New England mountains has received little attention since the early 1950s. U.S. Air Force, Harvard University and Mount Washington Observatory studies have not been continued (Burhoe 1948, Whipple 1948, Boucher 1950).

Mountain atmospheric icing occurs principally in two forms: glaze and rime. Glaze is produced when falling raindrops striking subfreezing surfaces form a nearly continuous, hard, usually clear and homogeneous ice film. Droplets creating glaze usually fall through inversions, frequently within warm fronts, causing them to supercool. Glaze is bubble-free because latent heat is liberated relatively slowly, producing ice densities approaching 0.9 g/cm$^3$ (Bennett 1959, Minsk 1980, Stewart and King 1987).

Rime is more common in the mountains of New England and is not a result of precipitation but is frequently associated with it (Boucher 1949). It forms when supercooled cloud droplets carried by the wind strike subfreezing objects, accreting horizontally rather than vertically on the upwind sides of objects that are aerodynamically efficient collectors. Densities vary from 0.1 g/cm$^3$ for soft rime to about 0.8 g/cm$^3$ for hard rime. Soft rime results when freezing cloud droplets liberate latent heat rapidly, producing a pure white, delicate, feathery structure. Hard rime, liberating latent heat more slowly, is also usually opaque and milky in appearance but with a less detailed and more subdued feathery structure (Minsk 1980).

Studies on Mount Washington in the 1940s found icing most frequent in the late fall and early spring, with a midwinter decline (Conrad 1948). Maximum ice accumulations formed most often in early morning and least often in midafternoon. Most icing on Mount Washington occurred in Continental Polar air, with frequent icing after cold fronts. Icing was most persistent in occluded fronts (Whipple 1948). Cyclones associated with icing were usually located in southern and central Quebec, with a secondary maximum about 640 km east-northeast of Mount Washington (Boucher 1949). Ryerson (1987) found similar conditions on Mount Mansfield in Vermont. Boucher (1949) indicated a need to study in more detail the effect of fronts on icing and to distinguish between types of icing storms.

This study further addressed the climatology of atmospheric icing on Mount Mansfield in northern Vermont and Mount Washington, New Hampshire, using a longer and more recent record of icing observations. The specific goals were

- to analyze the frequencies, intensities, lengths, accretion amounts and return intervals of icing events on two mountains with different summit elevations;
- to characterize in map form the synoptic climatology of New England mountain icing.

## STUDY LOCATION AND PERIOD

Mount Mansfield (44°30′N, 72°45′W) in the Green Mountains of Vermont and Mount Washington (44°15′N, 71°15′W) in the White Mountains of New Hampshire are located approximately 127 km apart (Fig. 1). With elevations of 1339 and 1917 m, respectively, Mount Mansfield and Mount Washington are ideal mountain icing study sites for several reasons:

- They have frequent icing events for at least three seasons.
- They have continuously manned summit facilities for instrumentation.
- They have four years of concurrent icing records from the same model of ice detector (Tucker and Howe 1984, Ryerson 1987).
- They have daily weather records.
- They are in similar meteorological environments. However, Mount Washington is influenced to a greater extent by oceanic

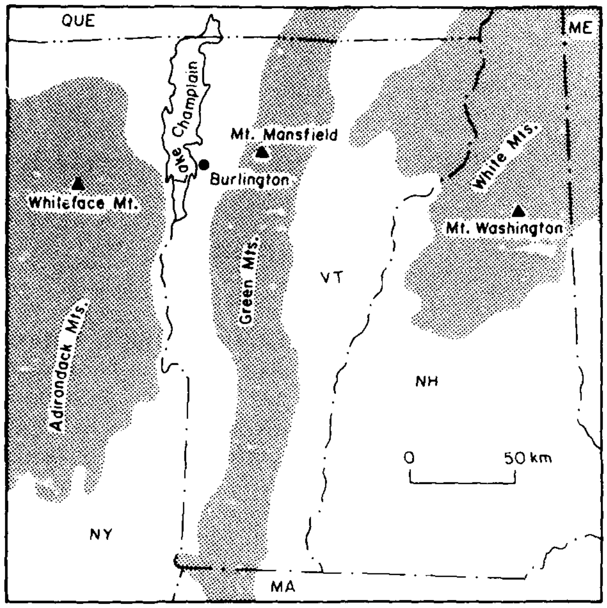



*Figure 1. Locations of Mount Mansfield and Mount Washington.*

moisture and by fall and early winter coastal storms. Mount Mansfield probably experiences a greater impact from late fall and early winter moisture advected from as-yet unfrozen Lake Champlain and the Great Lakes.

- They are situated in similar topographic environments. Though Mount Washington is higher, both peaks are prominent at their locations, are situated within north-south trending ranges, and are relatively unprotected from prevailing weather (Burt 1960, Hagerman 1971, Meeks 1986, Van Diver 1987).
- They are sufficiently different in elevation at their peaks (578 m), where ice detectors are located, yet similar synoptically for a comparison of the effect of elevation on icing incidence and severity.

The study covers portions of four winter seasons from December 1982 through April 1986. Though a longer period would be preferable, a four-year record is acceptable for characterizing mountaintop icing (Hoffer et al. 1981) (Fig. 2, Table 1).

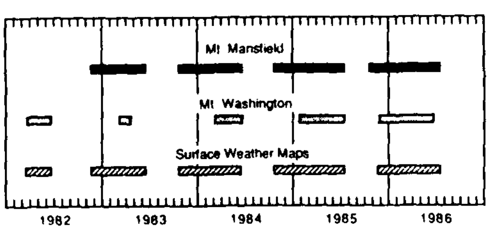



*Figure 2. Icing and weather data correspondence.*

**Table 1. Mount Mansfield and Mount Washington icing data collection record. Gaps of six hours or less are ignored.**

| Beginning of icing Date | Time (GMT) | End of icing Date | Time (GMT) |
|---|---|---|---|
| **Mount Mansfield** | | | |
| 10 December 82 | 1400 | 9 January 83 | 0300 |
| 14 January 83 | 1200 | 25 February 83 | 0400 |
| 26 February 83 | 0100 | 6 April 83 | 0800 |
| 10 April 83 | 1800 | 8 May 83 | 1200 |
| 29 October 83 | 1800 | 22 May 84 | 2400 |
| 21 October 84 | 0100 | 21 December 84 | 1300 |
| 22 December 84 | 2000 | 18 February 85 | 0100 |
| 24 February 85 | 1900 | 20 May 85 | 2400 |
| 2 November 85 | 1700 | 26 April 86 | 0500 |
| 27 April 86 | 1500 | 26 May 86 | 1600 |
| **Mount Washington** | | | |
| 6 March 82 | 0100 | 14 May 82 | 2400 |
| 23 January 83 | 0100 | 25 January 83 | 2100 |
| 27 January 83 | 0700 | 8 February 83 | 2200 |
| 17 February 83 | 0700 | 18 February 83 | 0900 |
| 7 March 83 | 1400 | 8 March 83 | 2400 |
| 20 February 84 | 0100 | 29 May 84 | 2400 |
| 27 December 84 | 0100 | 15 June 85 | 2400 |
| 24 November 85 | 0100 | 9 May 86 | 2400 |

*Figure 3. Rosemount Model 871CB1 ice detector on Mount Washington.*

## DATA

### Ice detection

The time and intensity of icing on Mount Mansfield and Mount Washington were detected with Model 871CB1 Rosemount ice detectors. The 871 CB1 detector, replaced by the current Model 872 B12, was designed to operate in intense radio frequency environments for activating broadcast antenna heaters at the onset of icing. The unit consists of a 14.5-cm-long by 8.1-cm-wide by 6.4-cm-high stainless steel box topped by a 6.4-cm-diameter hemisphere. A 0.6-cm-diameter by 2.8-cm-long nickel-plated ice-sensing probe protrudes from the top of the dome and extends an equal distance beneath the dome into the box (Rosemount Engineering Co. 1982)(Fig. 3). The ice-sensing probe operates on the principal of magnetostriction by lengthening and shortening axially at 40 kHz. The opposite ends of the probe exhibit the largest motion, which cannot be felt, with the node where no axial motion occurs located at the point where the probe enters and is brazed to the dome.

The 40-kHz natural ice-free frequency is a function primarily of the stiffness and mass of the probe. Changes in the mass of the probe, or the stiffness through accidental bending or cracking of the metal, will change its natural frequency. An increase in the mass of the probe decreases the natural frequency; a decrease in mass increases the frequency. As ice accretes on the probe, the frequency drops until its reaches a factory-preset value, 180–200 Hz below the rest frequency.* At approximately 39,800 Hz a timer-controlled deicing cycle begins, heating the probe and dome for 90 s. A 115-V AC deicing signal is concurrently sent to antenna heater relays or, on Mount Mansfield and Mount Washington, to a Rustrak strip-chart event recorder.

The mass of ice, and thus the thickness at a given density, necessary to start a deicing cycle is controlled largely by the difference between the natural uniced probe frequency and the frequency initiating the heating cycle. Subtle or catastrophic changes in the control electronics or the mass or stiffness of the probe with time can cause the factory calibration of the 871CB1 detector to change. A decrease in the frequency drop necessary to initiate a deicing cycle should decrease the mass necessary to start the heater.

Ice monitoring began on both mountains in December 1982 and continued until April 1986, with breaks during summers and instrument failures. The ice detector on Mount Mansfield is owned and operated by Vermont Educational Television (VTETV) and is mounted on a boom 1 m outside of the northwest corner of a microwave tower and about 10 m above ground level (detector elevation 1235 m) (Ryerson 1987). The Mount Washington detector is owned by Mount Washington Observatory and is mounted atop the Observatory tower about 15 m above ground level (Tucker and Howe 1984) (Fig. 3). Both ice detectors were operated for several years before the recorders were connected, but their calibration had not been checked because they were being used primarily for deicing antennas and anemometers—uses for which precise calibration is not necessary. In addition, monitoring was started on each mountain by different groups with no intention, at the time, of comparing them. Therefore, calibration checks were considered unnecessary.

*Ice detector calibration*

Concern was first raised about the calibration of the two ice detectors when this study was begun by Ryerson (1987). Tucker and Howe (1984) computed the accretion mass per deicing cycle of two models of Rosemount ice detectors (including the 871CB1) on Mount Washington from liquid water content and wind speed measured at the Mount Washington Observatory. Ryerson (1987) com-

* Personal communication with W. Hershey, Rosemount Inc.

puted the accreted mass per deicing cycle of the Mount Mansfield detector by comparing the mass that accreted on an adjacent homemade ice collector with deicing cycles occurring in the same period of time. There were no statistically significant differences in the mass per deicing cycle responses of the Model 871CB1 Rosemount ice detectors on the two mountains.

More recent concerns prompted additional calibration checks. The concerns included comparability of the instruments, drift of calibration with time, and mass accreted per cycle. Drift was of particular concern because the Mount Mansfield detector did not fail over the entire period of record, whereas the Mount Washington detector failed in March 1983 and at the end of the study in 1986 and was recalibrated at the factory at each repair.

Four techniques were used to answer these concerns:

- The mass accreted per deicing cycle for each period between failures of the Mount Washington detector was computed, and each period was checked for gradual or catastrophic changes in calibration befo e failure.
- Ratios of the monthly sums of deicing cycles per mountain were computed to determine if the detector calibrations had drifted together or apart with time.
- The ice-free and deicing frequencies of each detector were measured.
- The Mount Washington detector was operated next to the Mount Mansfield detector on Mount Mansfield for over 200 hours of icing.

The mass accreted per deicing cycle of the Mount Washington detector was computed using independent measures of ice accretion on a rotating multicylinder operated by the Observatory (Howell 1951, Howe 1982). The rotating multicylinder consists of six cylinders ranging from 0.158 to 7.140 cm in diameter. It measures cloud liquid water content and median volume droplet size, and it does so with less than 10% error (Howell 1951). Cylinder number two on the multicylinder has a diameter of 0.5 cm, similar to the 0.6-cm diameter of the ice detector probe, especially after ice has accreted on the cylinder, making their collection efficiencies similar. The mass accreted on the ice detector probe was computed by dividing the ice mass on cylinder two by the number of concurrent deicing cycles of the ice detector for 208 sets of measurements over the four-year period. Corrections were made for the different lengths of cylinder two and the Rosemount probe.

Chi-square statistics showed no significant change of the accretion mass per cycle over the entire study period, and correlation regressions showed no significant drift with time between failures. The mean accretion mass per deicing cycle was 0.06 g. The calibration remained nearly constant throughout the four years of record, with no significant changes in response before or after failure. This also suggests that failures were catastrophic rather than gradual, and thus have an insignificant influence on icing rate measurements over the study period. Similar direct checks could not be made for the Mount Mansfield detector because multicylinder measurements are not made on that peak. Instead, indirect methods were used.

Ratios of Mount Washington to Mount Mansfield deicing cycles per month were computed for 12 winter months spanning four years to determine if the two ice detectors had drifted together or apart with time. Since the Mount Washington detector apparently did not change its calibration significantly with time, the ratios of cycling on the two peaks should not drift if the Mount Mansfield detector did not drift. The ratios would become larger with time if the Mount Mansfield detector became less sensitive (deiced with a larger mass), and smaller if it became more sensitive (deiced with a smaller mass). This ignores long-term drifts in weather conditions that could cause the detectors to respond differently. Mean ratios of deicing cycles per month were 11.8, with a -0.07 correlation with time. Though the ratios decrease slightly with time, suggesting an increase in the sensitivity of the Mount Mansfield detector, the drift is not statistically significant. Although only 12 months were compared and there may have been long-term weather changes, the calibration of the Mount Mansfield detector has probably remained fairly constant over the four years of this study.

Ice-free and deicing frequencies of the two detectors were checked repeatedly with a frequency counter connected to an inductive coil placed over the probes. The measurements indicate that the Mount Washington detector (rebuilt in March 1987) deices after a mean 164-Hz drop from the ice-free frequency, and the Mount Mansfield detector deices after a 111-Hz drop. The ideal factory-calibrated drop is 180–200 Hz. This suggests that the Mount Mansfield detector deices with a smaller mass of ice than the Mount Washington detector, producing more deicing cycles than the Mount Washington detector and exaggerating the amount of ice that accretes on Mount Mansfield.

Finally, the Mount Washington ice detector was mounted adjacent to the detector on Mount Mansfield, and over 200 hours of icing records were retrieved. During this period the Mount Mansfield detector cycled about 2.3 times for every Mount Washington detector deicing cycle. Though the ratio between the two detectors varied considerably over the 200 hours, it suggests that the Mount Mansfield detector cycles with about half the mass necessary to cycle the Mount Washington detector. As with the frequency drop measurements, these results show that the Mount Mansfield detector may make Mount Mansfield appear to be more similar to Mount Washington than it should, and it may exaggerate the amount of ice appearing to accrete on Mount Mansfield.

Though some of these calibration checks are indirect, they show that the Mount Mansfield detector does not respond identically to the Mount Washington detector in the same conditions. This contradicts the earlier calibration checks by Ryerson (1987) and Tucker and Howe (1984). The statistical analyses also suggest that the calibration disagreement may have remained fairly constant with time.

As a result of these uncertainties the two mountains are compared in this study in two ways using two assumptions: 1) that the detectors are identical and 2) that the Mount Mansfield detector is twice as sensitive as the Mount Washington detector. A 2.0:1 ratio is used instead of 2.3:1 to provide recalibrated values for the Mount Mansfield detector. The 2.3:1 ratio is probably an extreme that resulted from comparing the recently factory-rebuilt Mount Washington detector with the Mount Mansfield detector and may not be representative of the entire four-year record, especially if they have drifted apart over the study period.

In addition to exaggerating icing rates and ice accretion amounts, the over-sensitive Mount Mansfield detector also exaggerates icing event lengths, particularly when the event begins or ends gradually. Having a lower deicing cycle threshold, the Mount Mansfield detector indicates icing sooner than the Mount Washington detector as the icing intensity increases at the beginning of an event. A similar process occurs at the end of events and within short lulls during events. To address this problem, Mount Mansfield ice detector events were shortened mathematically. As a result of dividing the Mt. Mansfield deicing cycles per hour by two to correct the calibration, half cycles were created when the original number of cycles per hour was odd. Half cycles represent ice accreted on the probe but not in sufficient quantity to start a new cycle on a properly calibrated detector during that hour. Therefore, the half cycle, like the ice on the probe, persists until the next hour and is added to the following hour. If an event ends with a half cycle, that half cycle is dropped, because there is insufficient ice to initiate another deicing cycle. This process shortens events to the length that would be measured by the Mount Washington detector.

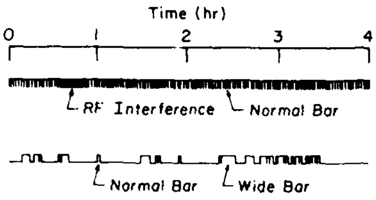
All unmodified Mount Mansfield deicing cycles are referred to throughout the analyses in this paper as the original calibration. All Mount Mansfield ice detector cycles modified to reflect the possible calibration changes are referred to as recalibrated. All comparisons are made with Mount Washington using both the original calibration and the recalibrated data.

*Additional ice detector concerns*

In addition to calibration questions, the manner of operating the detectors causes problems. The Mount Mansfield ice detector operated continuously without a break, except for occasional chart recorder failures, for each winter of the four years of the study. However, the Mount Washington ice detector was not operated when Observatory personnel judged that no icing was occurring, so data for these periods could have been inferred as missing. When icing was observed, the recorder was turned on, left on for the event duration, and then turned off.* Observers may have missed the beginning of some icing events, or perhaps entire minor events, because they were busy with other duties or could not see icing begin because of darkness. During data transcription from the recorder charts, periods between icing events when the ice detector was turned off were inferred as ice-free as judged by the Observatory personnel. Therefore, the data for the recorder off periods were not considered missing because of the ability and reliability of the Observatory crew. Only for the summer and for periods when the detector was removed for repairs were the data treated as missing.

Two additional problems contaminate the Mount Washington ice record. Television and radio transmission antennas on the mountaintop create a high-power radio-frequency (RF) environment. Though shielded against interference, the Rosemount can respond erratically when RF signals penetrate its shielding. The resulting high-frequency signal, readily apparent on the charts,

* Personal communication with J. Howe, Mount Washington Observatory.




*a. RF interference.*

*b. Wide bars created by overlapping deicing cycles.*

*Figure 4. Ice detector deicing cycle problems on recorder chart.*

occurred during 0.8% of the record period and 2.0% of the icing hours (Fig. 4a).

The second problem involves the 90-s deicing cycle of the Rosemount Model 871CB1 ice detector. Because of the constant 90-s heating period, fewer than 40 discrete deicing cycles can occur per hour when the detector is operating at its maximum rate. Higher icing rates and extreme cold and high winds apparently can cause deicing cycles to overlap because all of the ice cannot melt from the probe, causing detector saturation (Tucker and Howe 1984).

These overlapped deicing cycles do not record as discrete cycles, but as bars wider than one 90-s cycle. The wide bars occurred during 3.5% of the record period and 9.4% of the icing hours (Fig. 4b). Extremely high winds and low temperatures may not allow all the ice to melt from the probe and the dome, leaving a bead of water between the remaining ice and the probe. When the heater stops, the water refreezes and prematurely initiates another deicing cycle. Because of the extreme conditions that cause this phenomenon and the location of the ice detectors, observers cannot regularly and safely watch the premature deicing. If it did occur, it represents error that cannot be detected in the data.

Each data problem was transcribed differently from the strip charts. Periods of RF interference were removed from the record, and wide bars were counted as equivalent to the rates occurring before and after the bar. These problems were not as apparent at Mount Mansfield, probably because icing is less severe there.

Finally, in addition to these problems, the detectors can occasionally be bridged over with snow or rime, completely enveloping the instrument in a hollow cocoon and preventing it from detecting ice. When observed, these periods were removed from the record.

*Computation of icing rates from deicing cycles*

The Rosemount ice detector deices when a specific mass of ice, and thus thickness at a given density, accretes on the probe. As a result, Rosemount deicing cycles may serve as measures of ice accretion on objects with similar exposure and collection efficiency. However, measured deicing cycles cannot represent ice accretion amounts or icing rates without accounting for the time when the ice detector probe is deicing and not accreting ice. This is because the actual icing rate is the product of the probe-swept area, the collection efficiency, the wind speed and the cloud supercooled liquid water content. As the deicing cycle rate increases, the portion of time remaining for ice accretion on the unheated probe between deicing cycles decreases. Therefore, the actual rate of icing, and the amount of ice accreted over time, is not linearly proportional to the measured deicing cycles. This is not a serious problem at low icing rates because deicing consumes only a small portion of each icing hour. However, at high icing rates, a larger portion of each hour may be consumed for deicing than for icing.

A method for converting measured deicing cycles to icing amounts and rates actually experienced by the environment follows:

$$PC = MC \times \{1.0 + [MC/(40.0\text{-}MC)]\} \quad (1)$$

where $PC$ is the proportional deicing cycles per hour, and $MC$ is the measured deicing cycles per hour. Since the deicing cycle is factory-set to a constant 90-s length (as also measured on the Mount Mansfield and Mount Washington detectors), a theoretical maximum of 40 cycles can occur per hour with infinitely short accretion periods between deicing cycles. Equation 1 considers that portion of each hour devoted to deicing and computes a proportional cycling rate for a probe with an instantaneous, infinitely short deicing cycle that does not subtract from the probe accretion time. The equation assumes that the probe heats, deices, and cools instantly to the ambient air temperature and provides the maximum icing rate that could occur on a bare ice detector probe. It assumes that ice accretes on the probe during deicing cycles at the same rate that it accretes between deicing cycles. Except for rate variations within each hour, this is more proportional to and representative of the true accretion rate experienced in the environment on objects with similar collection efficiencies.

Proportional hourly deicing cycles of the Mount Washington data and the original and recalibrated Mount Mansfield data are used in all comparisons of icing on the two peaks. The product of PC and the ice mass necessary to trigger the deicing cycle provides the potential mass accretion on the probe over time.

**Synoptic weather data**

Synoptic data—highs, lows and fronts—were traced from microfilmed North American Surface Charts from the National Climate Data Center, Asheville, North Carolina (NOAA 1982-1986). North American Surface Charts are available for the entire study period for every three hours.

## CLIMATOLOGICAL ANALYSIS OF MOUNTAIN ICING

All analyses are based on the Rosemount icing records. Since the records do not cover the entire icing season on either mountain, they are not representative of the entire icing season. Also, since the icing records of both mountains do not coincide exactly, only coincident records are used for comparison. Of 18,055 hours of records on Mount Mansfield and 12,368 hours on Mount Washington, 9,868 hours, or 55% and 80% of the icing records, respectively, coincide.

**Analysis of hourly icing**

The two mountains have considerably different hourly icing conditions (Table 2). Two situations are analyzed statistically: all hours of record including periods when no icing is occurring, and only those hours when icing is occurring.

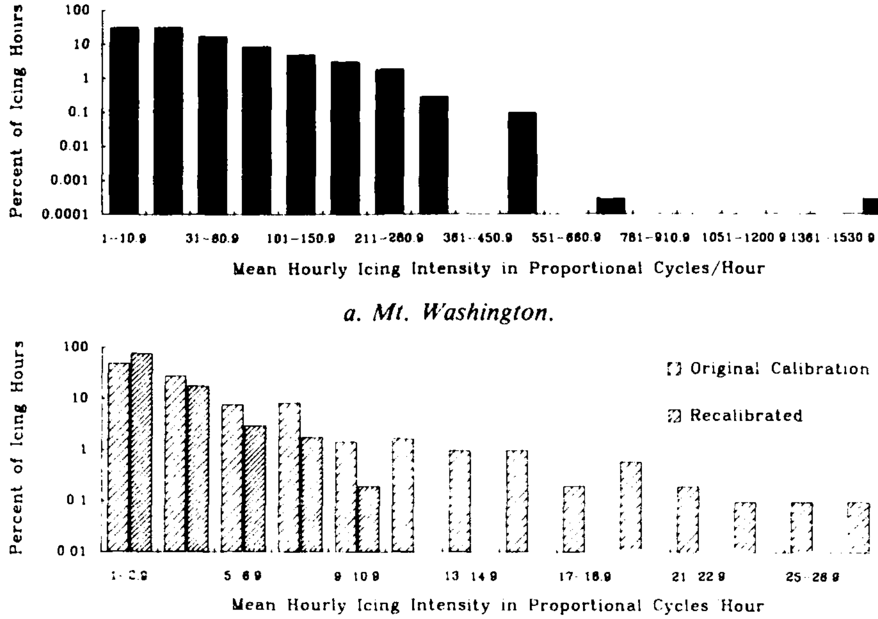
During the period of coincident records, icing occurred during 39% of all hours on Mount Washington and during 13-17% of all hours on Mount Mansfield. By comparison, Burhoe (1948) recorded ice during 28% of all hours on Mount Washington from January 1945 through January 1947, excluding June through October of all years and November of 1946.

Table 2 shows that on any given hour, Mount Washington mean icing rates are about 26-53 times more intense than Mount Mansfield rates. During icing, however, mean accretion rates are about 11-20 times greater on Mount Washington. Mount Mansfield is dominated by low-intensity events. Mount Washington experiences a far broader range of hourly icing intensities (Fig. 5). Correlations of the 9868 coincident hours of data from the two mountains may suggest whether similar mechanisms are causing icing on each. A high correlation may suggest that regional synoptic events, rather than orographic effects alone, are causing icing at the same time on both peaks. A low correlation might suggest different causes or may result only from the smaller frequency of icing events on Mount Mansfield.

The correlation of all icing intensities for the two mountains was only 0.25, significant at 0.000 probability. Correlations of high icing intensities alone were even lower. This may be due to timing when narrow, cold-front-generated disturbances

**Table 2. Hourly icing on both mountains for same hours of record in proportional Rosemount deicing cycles per hour.**

| | *Mt. Washington* | | *Mt. Mansfield* Original calibration | | *Mt. Mansfield* Recalibrated | |
|---|---|---|---|---|---|---|
| | *All hr.* | *Icing hr.* | *All hr.* | *Icing hr.* | *All hr.* | *Icing hr.* |
| Maximum | 1560.00 | 1560.00 | 27.00 | 27.00 | 10.00 | 10.00 |
| Minimum | 0.00 | 1.00 | 0.00 | 1.00 | 0.00 | 1.00 |
| Mean | 15.79 | 40.45 | 0.60 | 3.63 | 0.30 | 2.00 |
| Median | 0.00 | 19.00 | 0.00 | 3.00 | 0.00 | 2.00 |
| Mode | 0.00 | 7.00 | 0.00 | 1.00 | 0.00 | 1.00 |
| S. Dev. | 42.44 | 60.31 | 1.92 | 3.41 | 0.84 | 1.37 |
| Total hr. | 9868 | 3832 | 9868 | 1625 | 9868 | 1320 |
| % of hr. | 100 | 38.8 | 100 | 16.5 | 100 | 13.4 |




*a. Mt. Washington.*

*b. Mt. Mansfield.*

*Figure 5. Hourly icing intensity for icing hours on both mountains in proportional Rosemount deicing cycles per hour.*

pass consecutively over one mountain and then the other. However, correlations with 1- to 6-hour lag times between the two mountains produced insignificant changes. The correlations provide few clues to causative mechanisms.

Chi-square tests confirmed that the hourly icing rates on the two mountains are significantly different. The statistics support subjective observations that icing on Mount Washington is far more severe than on Mount Mansfield.

**Analysis of event icing**

Consecutive hours of ice accretion constitute an icing event. Ice-free periods between events are interevent periods. An event may have gaps, or nonaccretion periods, that are part of the event. The maximum number of consecutive nonaccretion hours imbedded within an icing event is defined in this study as one hour less than the minimum interevent period in hours. The interevent period length affects the frequency, length, intensity, ice accumulation and return period and thus the statistical climatological description of events.

Interevent periods during atmospheric icing are not addressed in the scientific literature. However, Thorp (1986) has studied interstorm periods for precipitation and suggested using seasonal precipitation meteorological characteristics to define the acceptable maximum number of dry hours within a storm. For example, he suggested that warm-season convective rainstorms may have 1- to 2-hour imbedded dry periods, whereas cold-season cyclonic and frontal storms may have up to 3-hour dry periods. Thorp did not base his dry period lengths on statistical analyses but instead chose logical, meteorologically reasonable lengths. He also demonstrated the effect of varying interstorm period lengths on storm parameters. Unlike precipitation, mountaintop icing may result from either storms or orographically induced fair-weather clouds. This study uses both statistical and meteorological approaches for finding a reasonable length for the period between icing events.

All periods with no ice accretion for 1 hour or more on both Mount Mansfield and Mount Washington were compiled into interevent periods (Table 3). Both mountains have similar interevent period characteristics. Minimums and modes are identical for both mountains, and means, medians and maximums are similar. For example, both mountains had median interevent periods of 7-8 hours, and Mount Mansfield and Mount Washington had mean interevent periods of about 25 and 19 hours, respectively. The majority of interevent periods on both mountains are less than 20 hours long (Fig. 6).

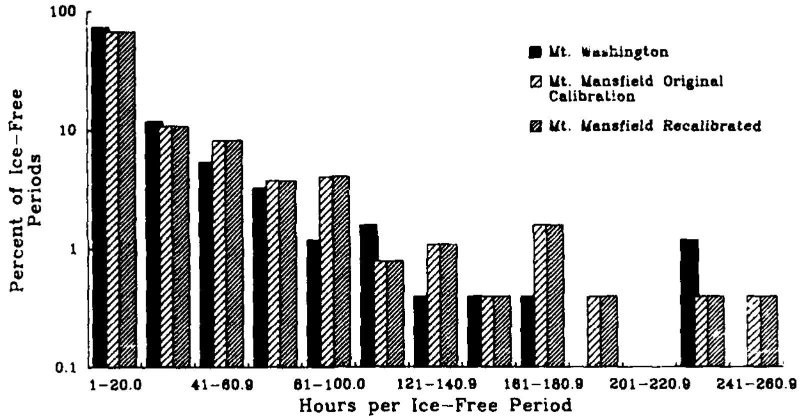



*Figure 6. Frequency of ice-free periods by length in hours.*

**Table 3. Interevent periods for both mountains (in hours) for the same period of record.**

| | Mt. Washington | Mt. Mansfield: Original calibration | Mt. Mansfield: Recalibrated |
|---|---|---|---|
| Maximum | 239.0 | 241.0 | 241.0 |
| Minimum | 1.0 | 1.0 | 1.0 |
| Mean | 19.2 | 24.5 | 25.5 |
| Median | 7.0 | 7.0 | 8.0 |
| Mode | 1.0 | 1.0 | 1.0 |
| S. Dev. | 34.51 | 39.71 | 45.0 |
| Total periods | 276 | 266 | 222 |

Event characteristics are a function of the minimum length of the interevent period separating them. Minimum interevent period lengths are a function of factors that tend to prevent clouds and icing, such as anticyclones. Winter anticyclones often linger over the Northeast for periods between the median and mean interevent period lengths of both mountains. Therefore, the median, mean and minimum interevent times were used to define events in this study.

As minimum interevent period lengths increase from one hour through the median and the mean on each mountain, mean event lengths and Rosemount proportional deicing cycles per event increase about 4-6 times (Table 4). Mean event icing intensities on each mountain remain nearly constant at approximately 12 proportional deicing cycles per hour on Mount Mansfield and 23-30 proportional deicing cycles per hour on Mount Washington.

The more intense icing environment on Mount Washington indicated in the hourly analysis is also apparent in the event analysis (Table 4). Events based on each of the three minimum interevent period lengths are about twice as long and about 12-20 times more intense on Mount Washington than on Mount Mansfield. In addition, Mount Washington events generate about 25-50 times more proportional Rosemount deicing cycles, suggesting that up to 25-50 times more ice may accrete per event on Mount Washington than on Mount Mansfield. Other than for interevent period lengths, which are similar, the high chi-square statistics and low probabilities in Table 5 indicate that the two mountains are most different with regard to event length, event intensity and deicing cycles per event. Both mountains are frequented by short events and interevent periods with generally little ice accretion per event (Fig. 7-9). But, as indicated in the hourly analysis, most Mount Mansfield events are of low intensity, whereas Mount Washington experiences a far broader range of intensities (Fig. 10).

Burhoe (1948) made similar observations of Mount Washington icing events for 14 months from January 1945 through January 1947. Using a 3- to 6-hour interevent period, he found that 14.6 icing events occurred each month on the average, with mean and median lengths of 14.1 and 9.0 hours and a maximum length of 75 hours. For the same interevent periods the data for 1983-1986 show an average of 15.1 icing events each month, with mean and median lengths of 20.5 and 13.5 hours and a maximum length of 171 hours. The differences may be due to the techniques used to measure ice events in the two studies—visual observations in the 1940s and Rosemount ice detectors in this study—or differences in icing climatology in the two periods.

**Table 4. Icing event and interevent comparisons by interevent length (in hours) for the same period of record on both mountains.**

| | *Max.* | *Min.* | *Mean* | *Median* | *S. Dev.* | *N* |
|---|---|---|---|---|---|---|
| **MT. WASHINGTON** | | | | | | |
| **One-hour interevent** | | | | | | |
| Event length | 101.0 | 1.0 | 12.2 | 8.0 | 13.30 | 273 |
| Event cycles | 11758.0 | 1.0 | 483.2 | 98.0 | 1011.91 | 273 |
| Event intensity | 170.4 | 1.0 | 23.4 | 12.5 | 28.53 | 273 |
| Interevent length | 239.0 | 1.0 | 19.2 | 7.0 | 34.51 | 276 |
| **Median interevent** | | | | | | |
| Event length | 171.0 | 1.0 | 25.2 | 18.0 | 28.41 | 134 |
| Event cycles | 11807.0 | 1.0 | 947.7 | 493.5 | 1513.32 | 134 |
| Event intensity | 170.4 | 0.4 | 30.1 | 19.4 | 31.57 | 134 |
| Interevent length | 239.0 | 7.0 | 35.9 | 21.0 | 42.48 | 139 |
| **Mean interevent** | | | | | | |
| Event length | 217.0 | 1.0 | 47.7 | 35.0 | 43.01 | 71 |
| Event cycles | 11807.0 | 1.0 | 1502.4 | 964.0 | 1944.42 | 71 |
| Event intensity | 137.60 | 0.7 | 30.4 | 21.3 | 26.76 | 71 |
| Interevent length | 239.00 | 19.0 | 55.9 | 39.0 | 48.61 | 77 |
| **MT. MANSFIELD (ORIGINAL CALIBRATION)** | | | | | | |
| **One-hour interevent** | | | | | | |
| Event length | 56.0 | 1.0 | 5.2 | 2.0 | 7.46 | 280 |
| Event cycles | 343.0 | 1.0 | 18.8 | 2.0 | 42.06 | 280 |
| Event intensity | 10.3 | 1.0 | 2.1 | 1.0 | 1.66 | 280 |
| Interevent length | 241.0 | 1.0 | 24.5 | 7.0 | 39.71 | 266 |
| **Median interevent** | | | | | | |
| Event length | 91.0 | 1.0 | 11.8 | 8.0 | 13.76 | 142 |
| Event cycles | 346.0 | 1.0 | 35.9 | 13.5 | 59.14 | 142 |
| Event intensity | 10.0 | 0.3 | 2.3 | 1.8 | 1.85 | 142 |
| Interevent length | 241.0 | 7.0 | 46.0 | 30.0 | 46.55 | 135 |
| **Mean interevent** | | | | | | |
| Event length | 140.0 | 1.0 | 26.4 | 19.0 | 26.35 | 77 |
| Event cycles | 347.0 | 1.0 | 60.6 | 33.0 | 76.35 | 77 |
| Event intensity | 10.0 | 0.1 | 2.4 | 1.8 | 2.02 | 77 |
| Interevent length | 241.0 | 25.0 | 71.4 | 52.5 | 48.54 | 76 |
| **MT. MANSFIELD (RECALIBRATED)** | | | | | | |
| **One-hour interevent** | | | | | | |
| Event length | 48.0 | 1.0 | 5.2 | 2.0 | 5.32 | 232 |
| Event cycles | 145.0 | 1.0 | 10.1 | 3.0 | 18.27 | 232 |
| Event intensity | 4.3 | 1.0 | 1.4 | 1.0 | 0.66 | 232 |
| Interevent length | 241.0 | 1.0 | 25.5 | 8.0 | 45.05 | 222 |
| **Median interevent** | | | | | | |
| Event length | 59.0 | 1.0 | 10.9 | 7.0 | 12.36 | 122 |
| Event cycles | 152.0 | 1.0 | 18.5 | 9.0 | 26.40 | 122 |
| Event intensity | 4.3 | 0.3 | 1.5 | 1.3 | 0.74 | 122 |
| Interevent length | 241.0 | 8.0 | 53.5 | 33.5 | 51.64 | 114 |
| **Mean interevent** | | | | | | |
| Event length | 120.0 | 1.0 | 22.2 | 16.0 | 22.84 | 74 |
| Event cycles | 152.0 | 1.0 | 28.6 | 15.5 | 33.65 | 74 |
| Event intensity | 4.3 | 0.1 | 1.4 | 1.2 | 0.89 | 74 |
| Interevent length | 241.0 | 26.0 | 78.0 | 60.5 | 52.68 | 70 |

**Table 5. Icing event and interevent independency by interevent length (hours) for same record period on both mountains.**

| | Original calibration | | | | Recalibrated | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Number of events | | | | Number of events | |
| | Chi square | Sig. | Mt. Mansfield | Mt. Washington | Chi square | Sig. | Mt. Mansfield | Mt. Washington |
| **One-hour interevent** | | | | | | | | |
| Event length | 61.78 | 0.000 | 280 | 273 | 48.61 | 0.000 | 232 | 273 |
| Event cycles | 155.66 | 0.000 | 280 | 273 | 155.70 | 0.000 | 232 | 273 |
| Event intensity | 233.99 | 0.000 | 280 | 273 | 245.33 | 0.000 | 232 | 273 |
| Interevent length | 0.70 | 0.403 | 266 | 276 | 0.74 | 0.388 | 222 | 276 |
| **Median interevent** | | | | | | | | |
| Event length | 25.71 | 0.000 | 142 | 134 | 27.83 | 0.000 | 122 | 134 |
| Event cycles | 91.18 | 0.000 | 142 | 134 | 99.15 | 0.000 | 122 | 134 |
| Event intensity | 130.01 | 0.000 | 142 | 134 | 138.58 | 0.000 | 122 | 134 |
| Interevent length | 5.23 | 0.000 | 135 | 139 | 13.50 | 0.000 | 114 | 139 |
| **Mean interevent** | | | | | | | | |
| Event length | 14.08 | 0.000 | 77 | 71 | 21.74 | 0.000 | 74 | 71 |
| Event cycles | 73.70 | 0.000 | 77 | 71 | 81.31 | 0.000 | 74 | 71 |
| Event intensity | 84.14 | 0.000 | 77 | 71 | 91.44 | 0.000 | 74 | 71 |
| Interevent length | 11.83 | 0.000 | 76 | 77 | 14.93 | 0.000 | 70 | 77 |

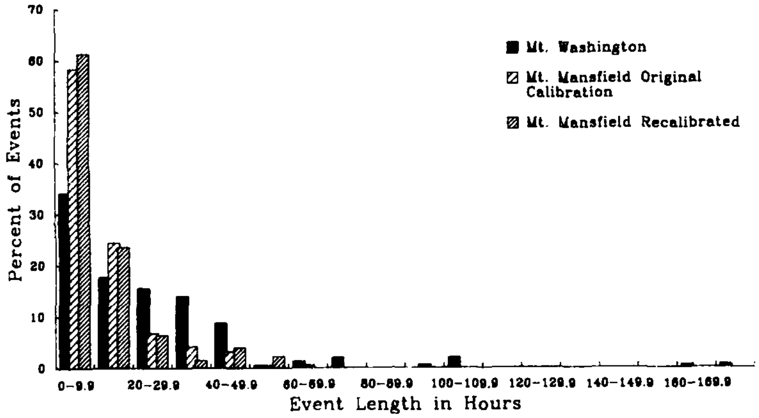



*Figure 7. Frequency of icing events by length based on the median minimum interevent period.*

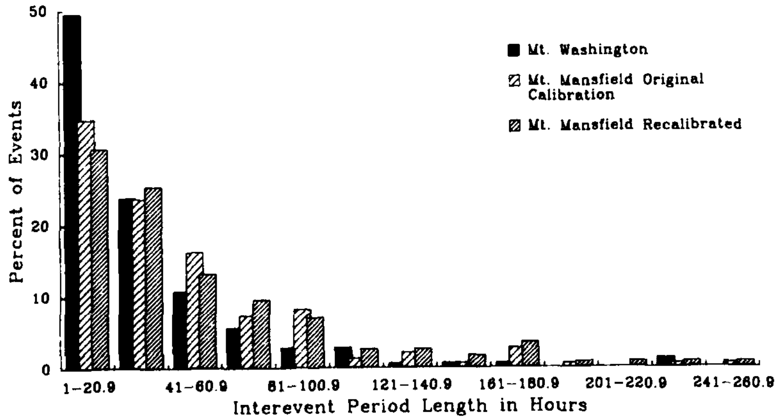
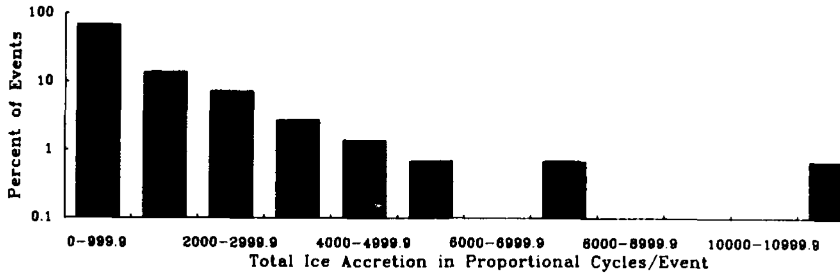
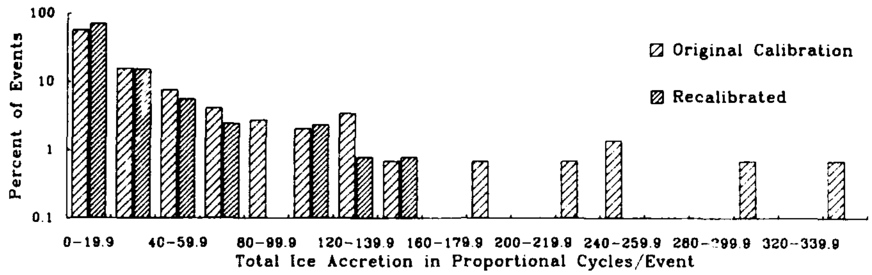



*Figure 8. Frequency of interevent periods by length based on the median minimum interevent period.*

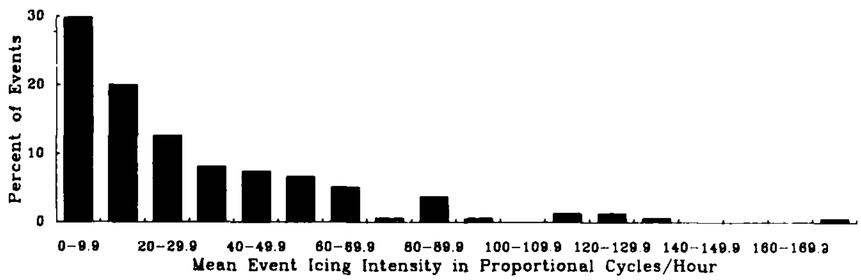



*a. Mt. Washington.*

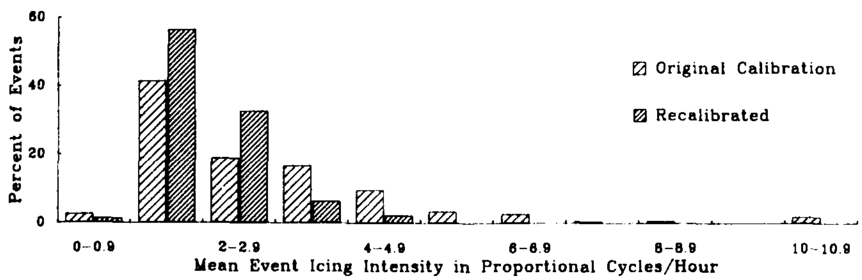



*b. Mt. Mansfield.*

*Figure 9. Frequency of icing events by accretion amounts in proportional Rosemount deicing cycles per event based on the median minimum interevent period.*

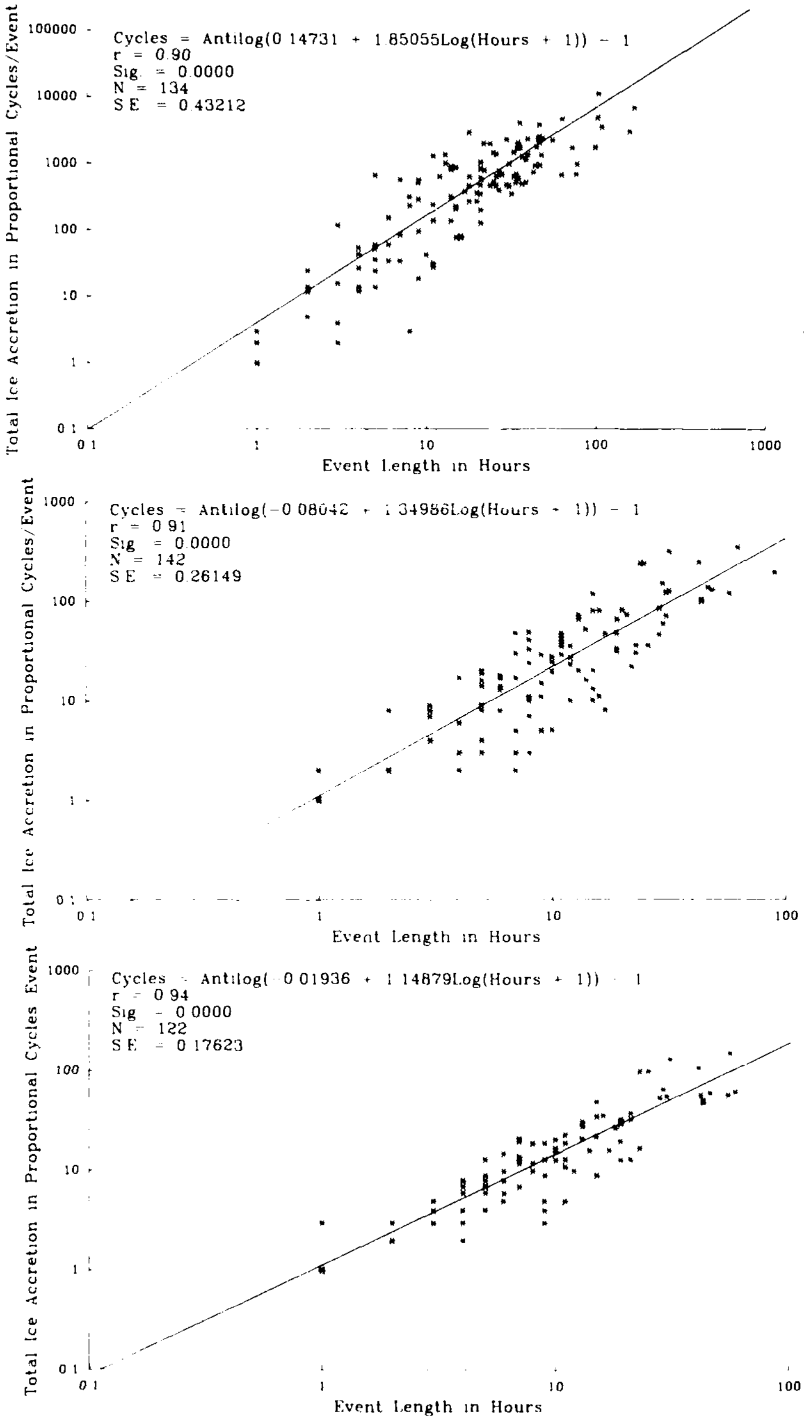



*a. Mt. Washington.*




*b. Mt. Mansfield.*

*Figure 10. Frequency of icing events by intensity in proportional Rosemount deicing cycles per hour based on the median minimum interevent period.*



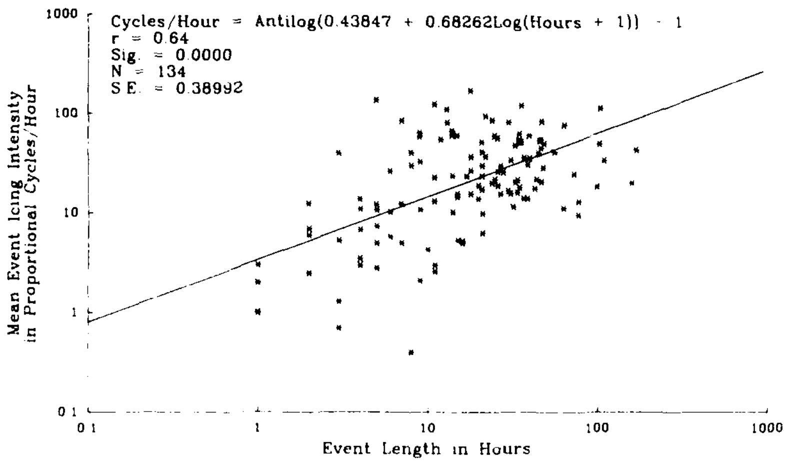

*a. Mount Washington.*

*b. Mount Mansfield (original calibration).*

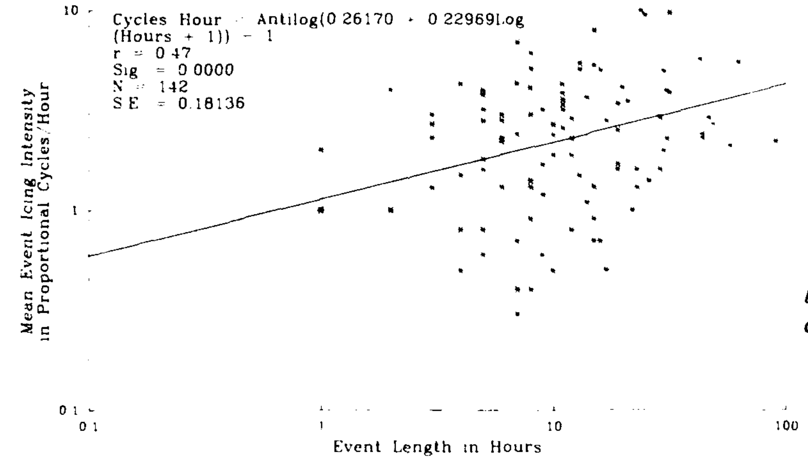
*c. Mount Mansfield (recalibrated).*

*Figure 11. Icing event length versus accretion in proportional Rosemount deicing cycles based on the median minimum interevent period.*

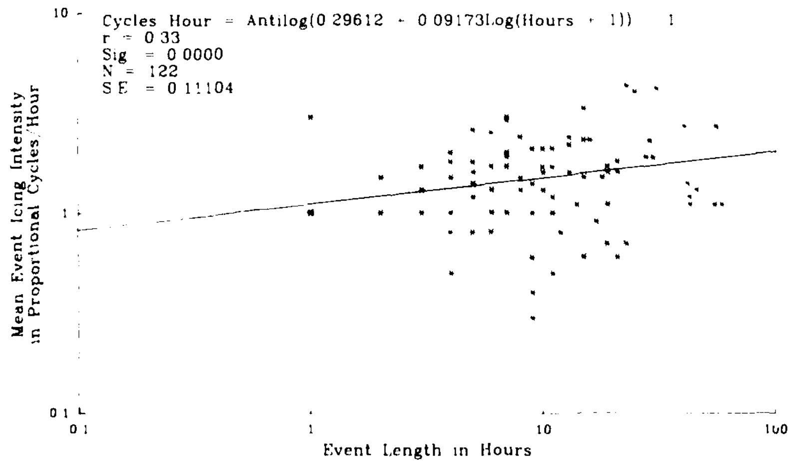
Events defined by a minimum interevent period length equal to the median on each mountain reveal several relationships between event length, event mean intensity and total ice accumulation per event (total proportional Rosemount deicing cycles per event). All of the relationships are log-normal. In Figures 11a and c, correlations between event length and the number of proportional Rosemount deicing cycles per event (ice accumulation) are remarkably similar for the two mountains. The strong relationships ($r$ = 0.90 to 0.94) between the common logarithm of both




*a. Mount Washington.*



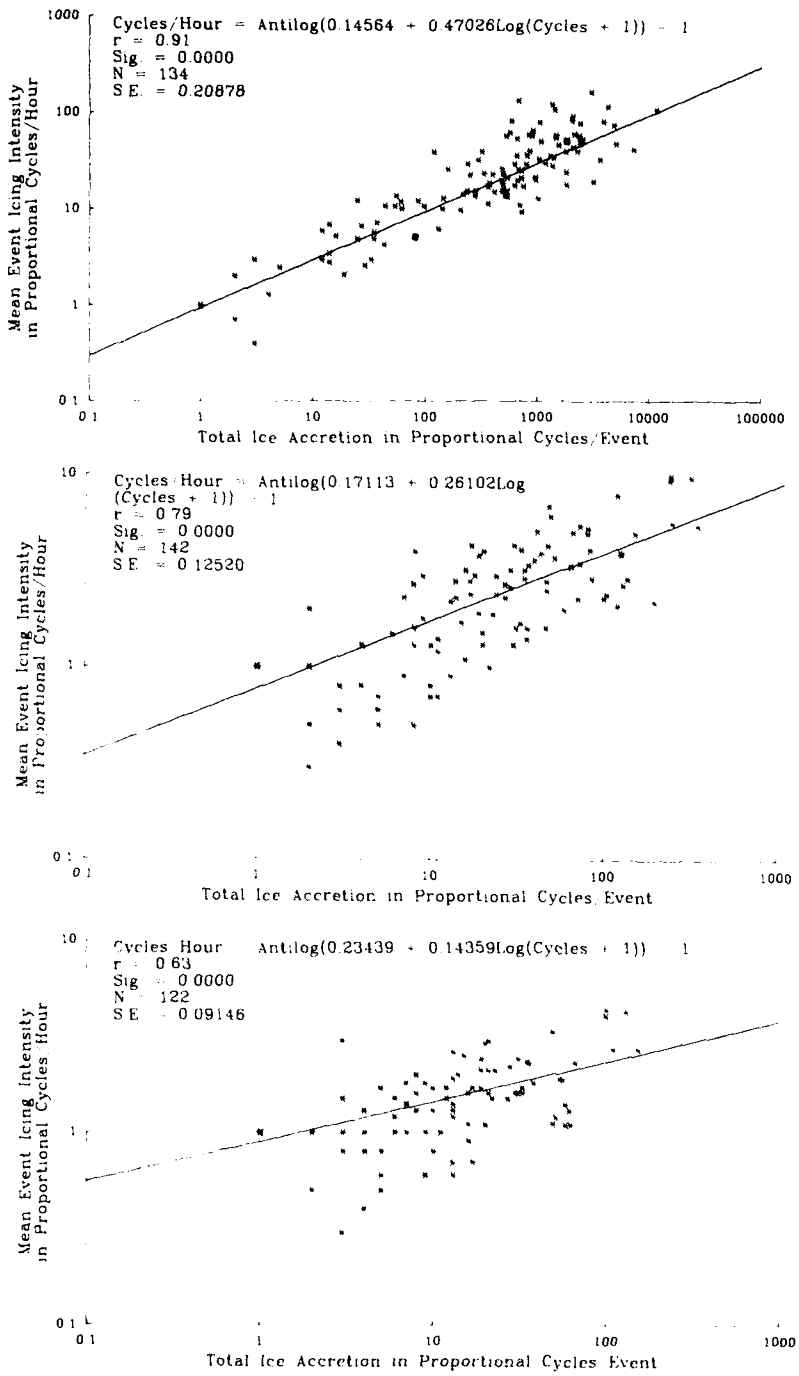

*b. Mount Mansfield (original calibration).*




*c. Mount Mansfield (recalibrated).*

*Figure 12. Icing event length versus intensity in proportional Rosemount deicing cycles per hour based on the median minimum interevent period.*

event length and ice accumulation suggest that the latter is largely a function of time. Figures 12a–c indicate that the relationships between the common logarithms of event intensity and event length are relatively weak on both mountains ($r$ = 0.33 to 0.64). Short events generally experience less-intense icing rates than long events. Finally, Figures 13a–c show that events with greater ice accumulations are also generally events with greater icing intensities ($r$ = 0.63 to 0.91). This suggests greater danger to structures because storms with the largest accumulations of ice may accrete at




*a. Mount Washington.*

*b. Mount Mansfield (original calibration).*

*c. Mount Mansfield (recalibrated).*

*Figure 13. Icing event accretion in proportional Rosemount deicing cycles versus intensity in proportional Rosemount deicing cycles per hour based on the median minimum interevent period.*

rates faster than ice alleviation methods can tolerate.

**Return intervals and probabilities**

As with floods, droughts and extremes of temperature, return periods or probabilities may be computed for icing events. Return periods indicate the frequency with which an event of a given magnitude should recur in a period. Though there are several methods of computing return probabilities, one of the most common is used here (Gumbel 1958):

$$P = m/(n + 1) \tag{2}$$

where $P$ = probability of event occurrence

$m$ = rank of event of given magnitude

$n$ = number of events.

The plots presented here for hourly icing intensities and events use a minimum interevent period equal to the median (Table 3).

Return period plots for all coincident record hours (Fig. 14) show that mean icing intensities of more than 2 proportional deicing cycles per hour on Mount Mansfield and 47 proportional deicing cycles per hour on Mount Washington are exceeded only 10% of the time. In addition, return plots for icing hours alone (Fig. 15) indicate that mean icing intensities of 4–8 proportional deicing cycles per hour on Mount Mansfield and 100 proportional cycles per hour on Mount Washington are exceeded only 10% of the time. Figures 14 and 15 also show that the probabilities are equivalent to

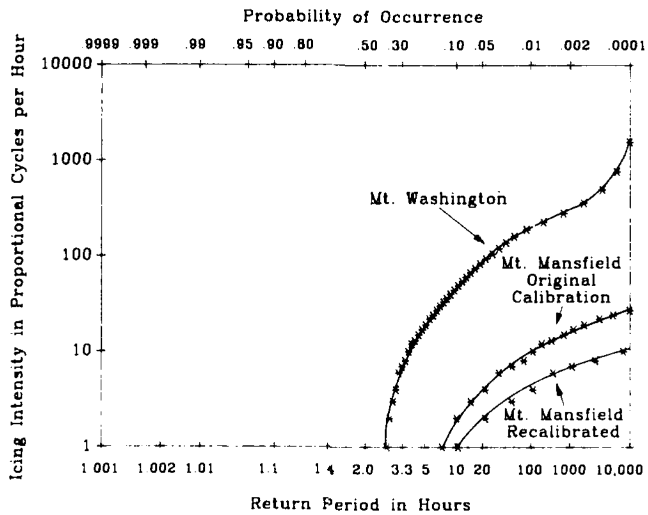



*Figure 14. Return probabilities for hourly icing intensity in proportional Rosemount deicing cycles per hour for any given hour of coincident record period.*

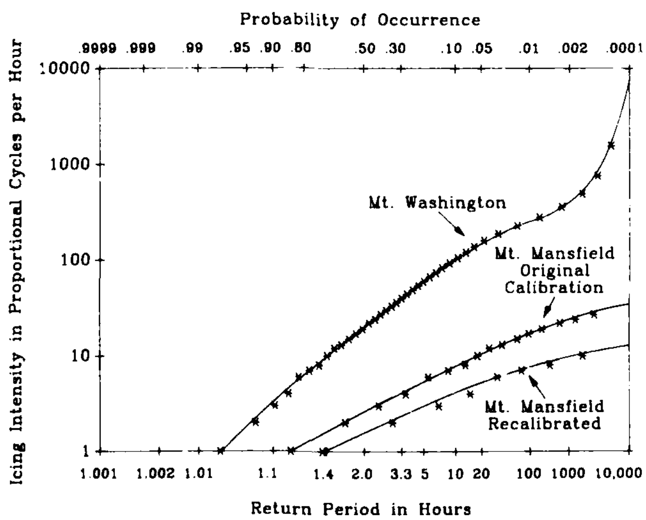



*Figure 15. Return probabilities for hourly icing intensity in proportional Rosemount deicing cycles per hour for hours of icing of coincident record period.*

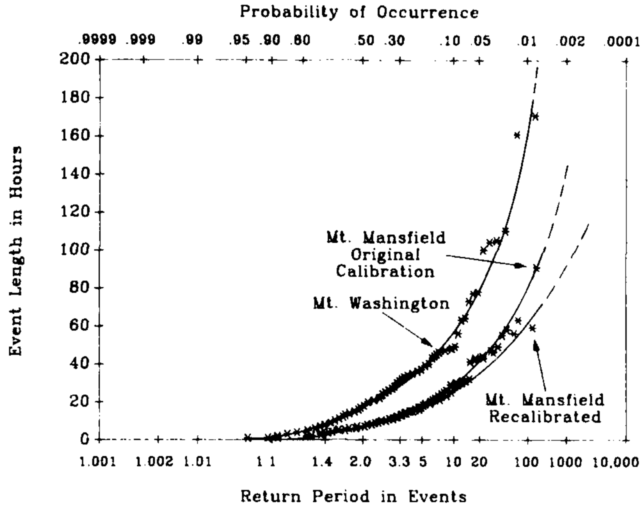



*Figure 16. Return probabilities for event length in hours for events based on the median minimum interevent period.*

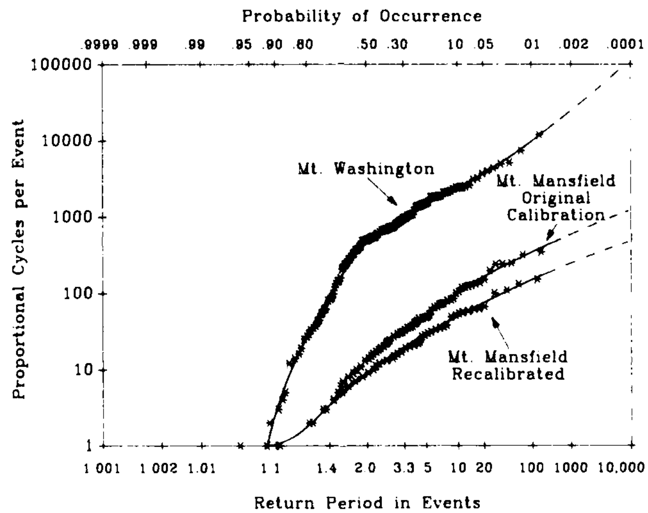



*Figure 17. Return probabilities for event ice accretion amounts in proportional Rosemount deicing cycles per event based on the median minimum interevent period.*

return periods: the above intensities are exceeded once every 10 hours on the average.

Figures 16–19 show return periods and probabilities for event characteristics. Half of all Mount Mansfield icing events are more than 7 hours long, produce more than 9-14 proportional deicing cycles, and exhibit mean intensities of 1.8 deicing cycles per hour or more (Fig. 16-18). In contrast, half of all Mount Washington events are more than 18 hours long, produce more than 494 proportional deicing cycles, and exhibit mean intensities of 19 proportional deicing cycles per hour or more. Finally, half of all interevent periods are more than 30 hours long on Mount Mansfield and 21 hours long on Mount Washington (Fig. 19).

The chances that extreme events not yet experienced may occur can be predicted by extrapolating. For example, Mount Mansfield did not experience an event longer than 91 hours. However, if the return period plot is extrapolated along the dashed line in Figure 16, Mount Mansfield could experience an event about 130 hours long every 1000 events.

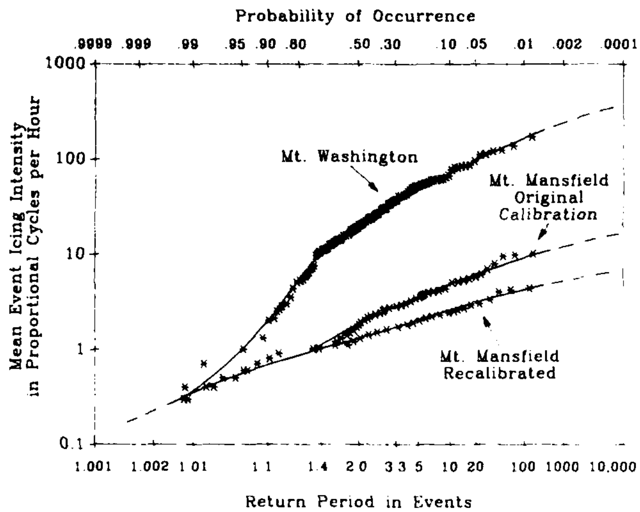



*Figure 18. Return probabilities for event icing intensity in proportional Rosemount deicing cycles per hour based on the median minimum interevent period.*

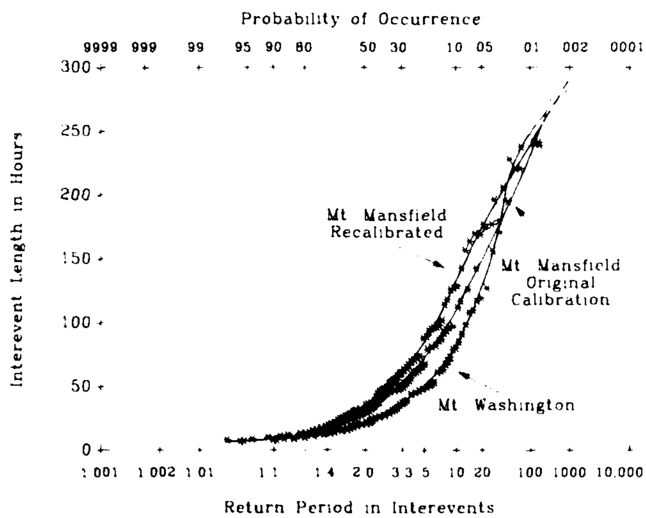



*Figure 19. Return probabilities for interevent periods by length based on the median minimum interevent period.*

**Ice accretion**

Potential ice mass and thickness that could accrete per event may be computed from the product of the mean accretion per proportional deicing cycle on the ice detector probe and the number of proportional deicing cycles per event. The mean mass accreted per proportional deicing cycle was computed from 208 concurrent multicylinder and Rosemount ice detector measurement periods at Mount Washington Observatory over the four-year study period and are described in the ice detector calibration discussion. The mean mass per proportional deicing cycle was 0.037 g/cm$^2$, which is valid only for objects with ice collection efficiencies similar to that of the ice detector probe.

Ice thickness was computed by dividing the ice mass by the mean ice density computed from multicylinder two over the four years of the study. This is valid, as indicated in the calibration discussion, because the ice detector probe and cylinder two have similar exposures, diameters, and thus collection efficiencies. A mean ice density of 0.67

**Table 6. Ice accretion per event by return period.**

| Return probability (%) | Accretion (kg/m²) | Thickness (mm) | No. of cycles |
|---|---|---|---|
| | **Mt. Washington** | | |
| 1 | 381.0 | 568.7 | 10243 |
| 5 | 139.8 | 208.7 | 3759 |
| 10 | 90.9 | 135.7 | 2444 |
| 25 | 45.2 | 67.5 | 1222 |
| 50 | 18.3 | 27.3 | 494 |
| 75 | 1.6 | 2.4 | 44 |
| 90 | 0.1 | 0.1 | 1 |
| | **Mt. Mansfield** | | |
| | *Original calibration* | | |
| 1 | 12.3 | 18.4 | 333 |
| 5 | 5.5 | 8.2 | 149 |
| 10 | 3.8 | 5.7 | 103 |
| 25 | 1.5 | 2.2 | 40 |
| 50 | 0.5 | 0.7 | 13 |
| 75 | 0.1 | 0.1 | 3 |
| 90 | 0.0 | 0.0 | 1 |
| | *Recalibrated* | | |
| 1 | 5.4 | 8.1 | 147 |
| 5 | 2.4 | 3.6 | 66 |
| 10 | 2.0 | 3.0 | 53 |
| 25 | 0.8 | 1.2 | 21 |
| 50 | 0.3 | 0.4 | 9 |
| 75 | 0.1 | 0.1 | 3 |
| 90 | 0.0 | 0.0 | 1 |

g/cm³ was computed for the 208 concurrent multicylinder-ice detector measurement periods. The potential ice mass and thickness by event are expressed by return probability in Table 6.

Table 6 indicates that 50% of all Mount Washington events accrete more than 18.3 g/cm² of ice and produce ice thicknesses greater than 27.3 cm. Mount Mansfield events accrete much less ice, with 50% of all events accreting more than 0.3–0.5 g/cm² of ice depending upon detector calibration, with thicknesses of 0.4–0.7 cm. At 50% probability, Mount Washington accretes about 37–61 times more ice than Mount Mansfield.

## SYNOPTIC CLIMATOLOGY OF ICING

A graphic analysis similar to that described by Muller (Muller 1977, Muller and Jackson 1985) was used to identify synoptic weather conditions during intense icing on Mount Mansfield and Mount Washington. North American Surface Charts, produced every 3 hours, were selected for hours when icing was intense (NOAA 1982–1986). Intense icing was defined as occurring when hourly measured Rosemount deicing cycle rates were greater than one standard deviation above the mean. Proportional deicing cycles were not used in selecting the weather maps, and Mount Mansfield maps were selected using the original calibration cycles.

To provide a large sample, all hours of record were analyzed, not just the coincident hours of record for the two mountains. This yielded 154 charts for Mount Mansfield and 270 charts for Mount Washington. Three analyses were performed. First, positions of pressure systems and fronts nearest to Mount Mansfield and Mount Washington were plotted to reveal patterns. Second, five synoptic types were identified by their frequency during intense icing. Third, paths of three major ice-producing storms were plotted and the sequence of events in each discussed.

### Pattern analysis

Figure 20 shows that lows are clustered, with foci approximately 400–450 km east of both mountains during intense icing. Though clustering is less evident with the Mount Washington storms, the patterns suggest that icing is most intense when lows are clustered offshore just south of Nova Scotia. Mount Washington Observatory (1950) reported that icing was most probable and heaviest when cyclone centers were 480–640 km north or northeast of the mountain in an area extending from the Gulf of Maine to the Nova Scotia coast.

Figure 21 shows that anticyclone patterns are less distinct. During intense icing, highs are rarely found to the southeast; most are located more than 450 km to the southwest or northwest. Highs to the west advect cold, dry continental air into residual maritime air from lows retreating over the North Atlantic, producing rime. Highs are less frequent to the southeast because they advect warmer maritime air into New England from that location. When it is cold enough, though, southerly winds can produce dense and destructive hard rime or clear ice.

Cold front patterns reflect the cyclone patterns (Fig. 22). Though quite scattered, they do cluster to the east of the mountains and reinforce the concept that cold continental air following the cold front is underrunning moist air wrapping around the cyclone to the north to produce high liquid water contents and ice.

As with cold fronts, warm fronts cluster to the

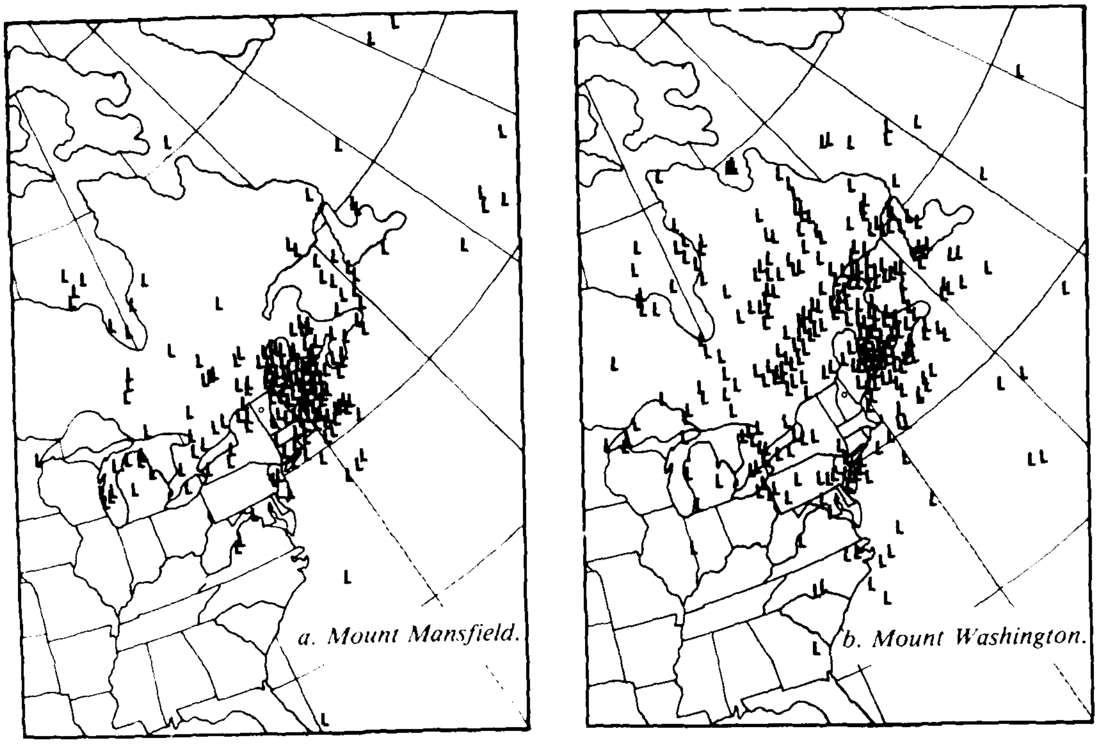



*Figure 20. Nearest lows during intense icing.*

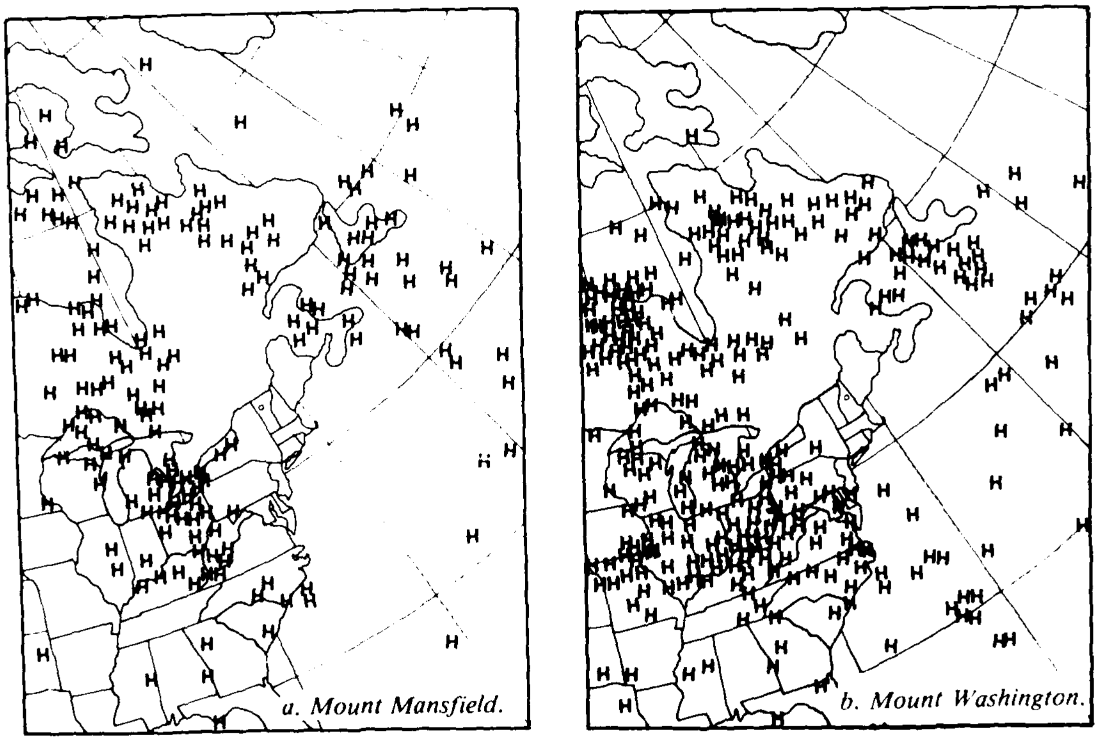



*Figure 21. Nearest highs during intense icing.*

*a. Mount Mansfield.* *b. Mount Washington.*

*Figure 22. Nearest cold fronts during intense icing. Dashed lines denote frontolysis.*

east of the mountains when icing is intense (Fig. 23). Though warm fronts are less likely to produce rime, their common location eastward of cyclones indicates that warm, moist air is being advected into the storm and above the colder continental air following the storm. Warm fronts to the west and southwest, and some from the southeast, do occasionally produce heavy rime and can produce high ice densities. According to Boucher (1950), some of the highest liquid water contents measured in clouds during icing at Mount Washington occurred when warm fronts extended along the coast.

Occluded fronts produce a pattern similar to that of lows because of their location near cyclone cores (Fig. 24). Stationary fronts, however, produce almost random patterns during intense icing events, an artifact of that type of front and not of its ability to create rime (Fig. 25). Since those fronts are stationary, significant amounts of moisture can be advected into their neighborhood. Their potential to generate mountaintop ice should not be discounted simply because a coherent pattern is not evident.

**Synoptic weather types**

This analysis suggests that distinct synoptic weather regimes, patterns or types can be identified as producing rime. All 424 surface charts were sorted into five weather types (Table 7). These weather types, though sometimes merging from one to another within a single storm passage, create different wind, humidity and temperature conditions at the mountaintops and therefore different ice types or intensities or both.

*Post Cold Front (PCF)*

Cold fronts are responsible for about 52% of all intense icing in the Green Mountains and White Mountains (Tables 7, 8). The cold front is always found within a few hundred kilometers to the east, and a cyclone is usually located to the northeast or north (Fig. 26). A high is usually located to the west, southwest or northwest, advecting cold, dry continental air into New England. Wind directions during icing are west to northwest. In an analysis of three years of data, Whipple (1948) found cold fronts and continental polar air associated with icing about two thirds of the time on Mount Washington.

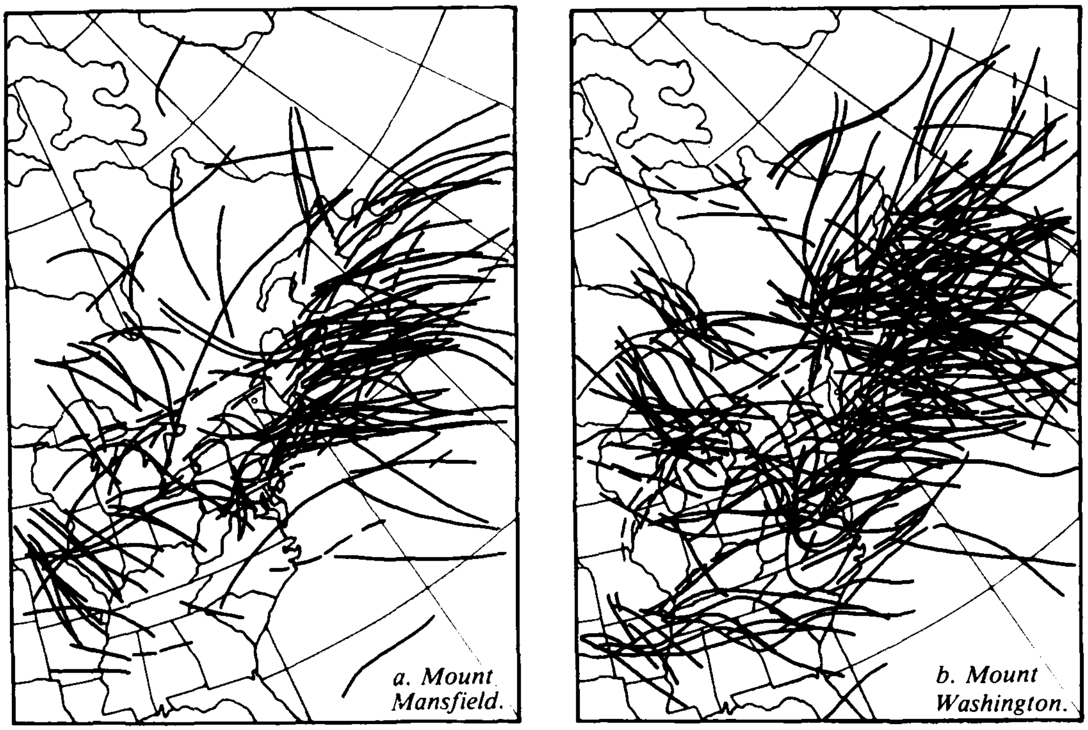



*Figure 23. Nearest warm fronts during intense icing. Dashed lines denote frontolysis.*

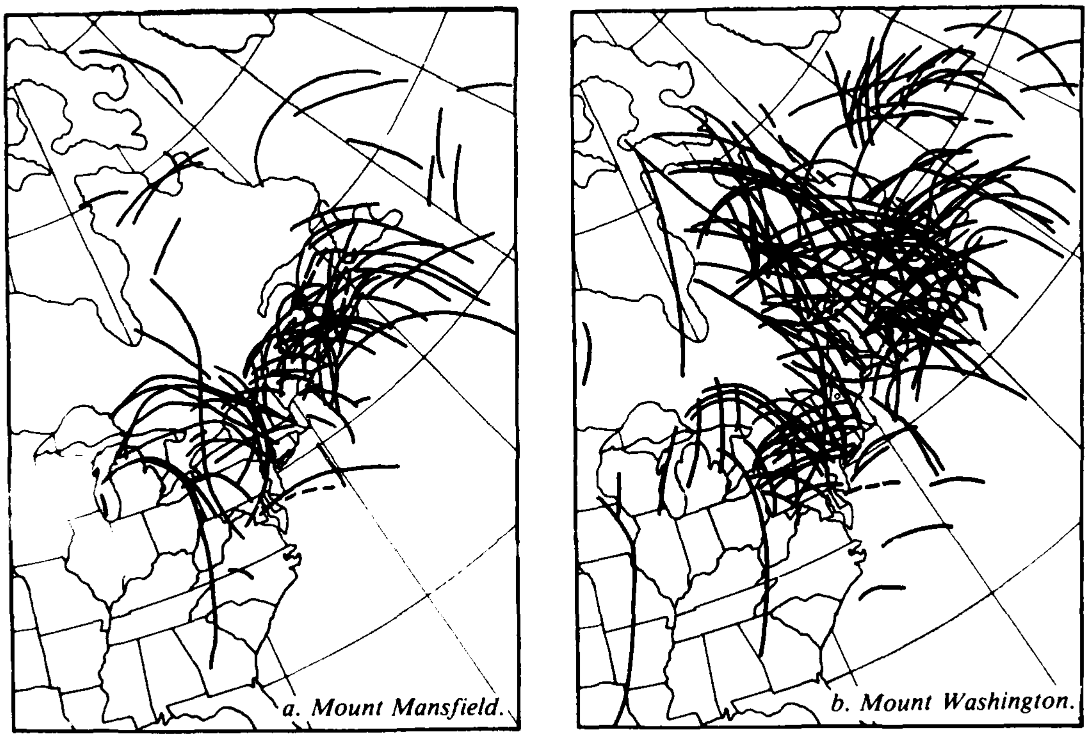
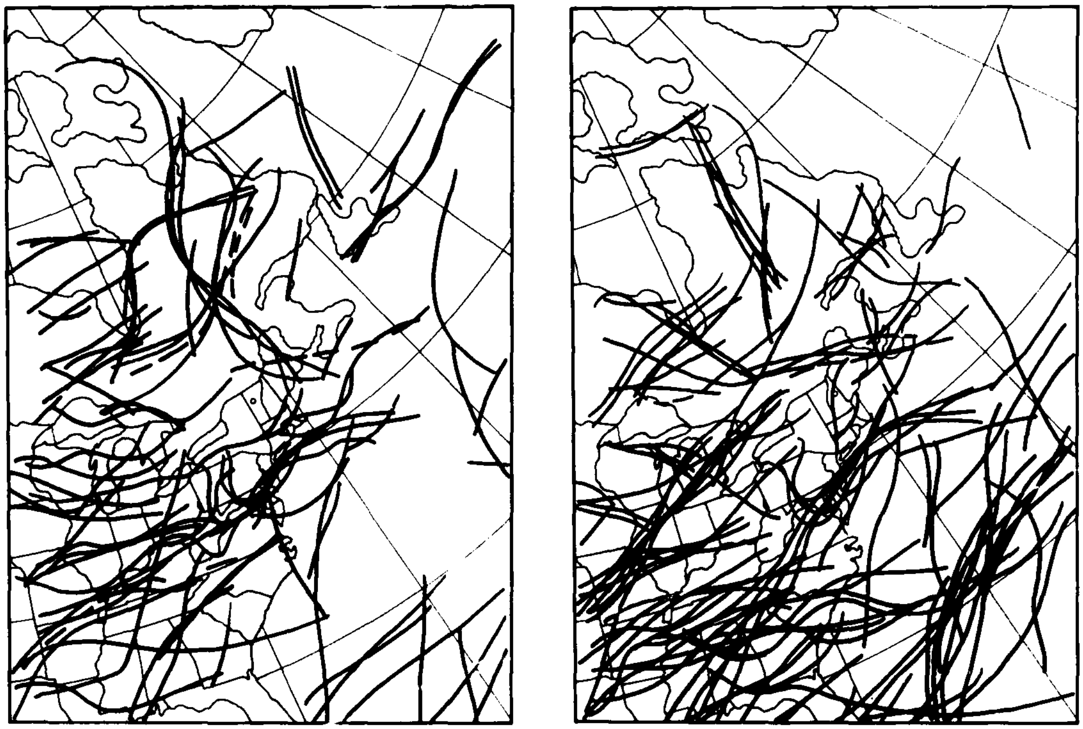



*Figure 24. Nearest occluded fronts during intense icing. Dashed lines denote frontolysis.*



a. Mount Mansfield. b. Mount Washington.

*Figure 25. Nearest stationary fronts during intense icing. Dashed lines denote frontolysis.*

**Table 7. Synoptic weather types producing severe icing.**

| | *Mt. Mansfield* | | *Mt. Washington* | | *Total* | |
|---|---|---|---|---|---|---|
| | *N* | *%* | *N* | *%* | *N* | *%* |
| Post cold front | 89 | 57.8 | 130 | 48.2 | 219 | 51.6 |
| Warm front to south | 35 | 22.8 | 56 | 20.7 | 91 | 21.5 |
| Multiple fronts or cyclones | 12 | 7.8 | 41 | 15.2 | 53 | 12.5 |
| Cold front to west | 9 | 5.8 | 27 | 10.0 | 36 | 8.5 |
| Miscellaneous | 9 | 5.8 | 16 | 5.9 | 25 | 5.9 |
| Total | 154 | 100.0 | 270 | 100.0 | 424 | 100.0 |

**Table 8. Surface weather means by synoptic type as measured at Mount Washington Observatory.**

| | *Rosemount proportional deicing (cycles/hr)* | *Temperature (°C)* | *Precipitation (mm)* | *Wind speed (m/s)* | *Wind direction (° azimuth)* |
|---|---|---|---|---|---|
| Post cold front | 123.3 | -10.9 | 0.7 | 29.1 | 281.1 |
| Warm front to south | 112.4 | - 6.9 | 2.3 | 26.8 | 198.4 |
| Multiple fronts or cyclones | 113.8 | - 9.7 | 0.5 | 25.0 | 268.0 |
| Cold front to west | 106.8 | - 8.8 | 0.6 | 27.3 | 260.9 |
| Miscellaneous | 121.6 | -11.1 | 0.7 | 27.0 | 284.4 |

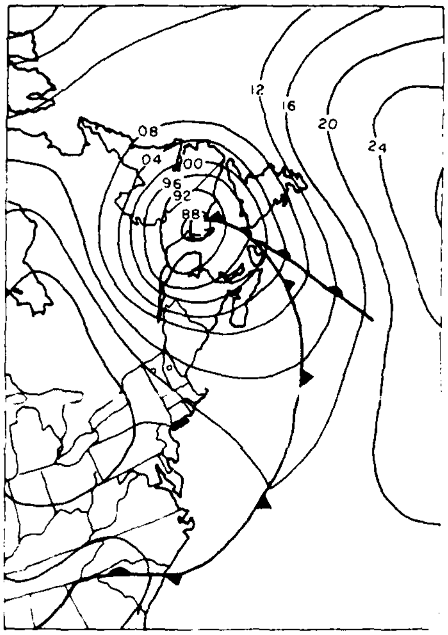



Figure 26. Post cold front (PCF) synoptic type.

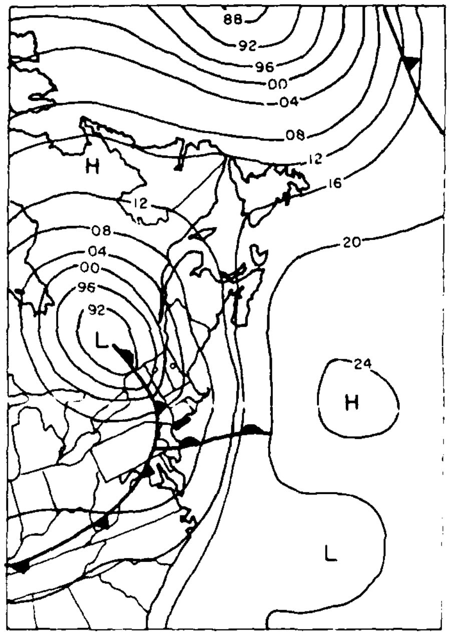



Figure 27. Warm front to south (WFS) synoptic type.

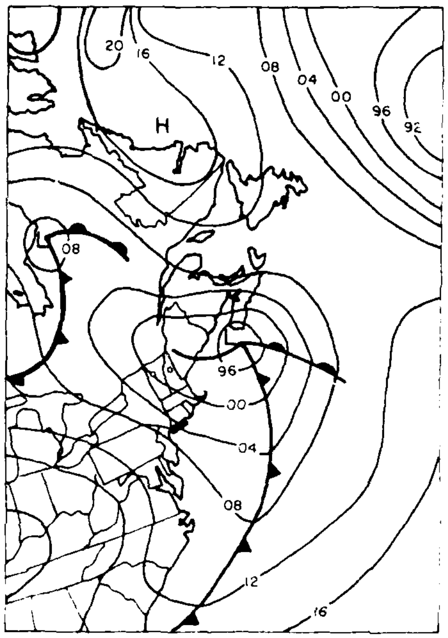



Figure 28. Multiple front or cyclone (MFC) synoptic type.

*Warm Front to South (WFS)*

Producing 22% of the intense icing on Mount Mansfield and Mount Washington, this pattern is the warmest in this study (Tables 7, 8). Temperatures average -6.9°C, and winds are southerly. The storm center is usually located to the north, with the warm front within a few hundred kilometers to the south and a cold or occluded front immediately to the west (Fig. 27). Whipple (1948) attributed Mount Washington icing to warm fronts and maritime polar air preceding warm fronts about 18% of the time.

*Multiple Fronts or Cyclones (MFC)*

About 13% of all icing events on the two mountains are produced by multiple cyclone centers or fronts in close succession (Tables 7, 8). One low is usually located offshore, and the second is frequently approaching the St. Lawrence Valley (Fig. 28). The closeness of weather-producing elements lengthens the icing period and complicates forecasting. Winds are usually westerly, and temperatures are low. The length of the storm, combined with two cyclones, produces large ice accumulations.

*Cold Front to West (CFW)*

The cold front to west, or warm-sector synoptic type, is typified by a cold front within a few hun-

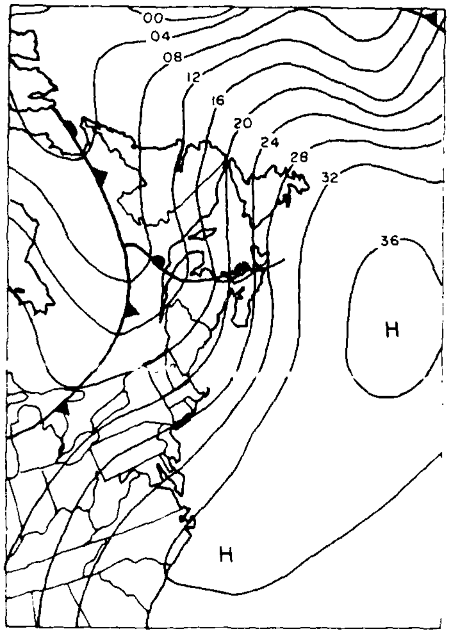



*Figure 29. Cold front to west (CFW) or warm sector synoptic type.*

dred kilometers to the west with a warm front usually to the north (Fig. 29). No cold front is within hundreds of kilometers to the east. Occurring only about 9% of the time, winds are west-southwest, and it is the second warmest of the storm types (Tables 7, 8). A high over the Atlantic Ocean typically advects moist air into the region along its western limb. Icing occurs within the maritime air in the warm sector of the storm. Whipple (1948) detected icing 8.2% of the time on Mount Washington during these conditions.

*Miscellaneous (MSC)*

No coherent pattern characterizes these systems responsible for about 6% of all intense ice events. They are, however, the coldest of all five storm types and exhibit northwesterly winds.

**Synoptic type classification analysis**

Since the five synoptic types were grouped subjectively, a statistical analysis was performed to determine if they were significantly different from one another with respect to meteorological variables measured at the ground surface. Rosemount deicing cycles and air temperature, wind speed and the trigonometric components of wind direction measured at Mount Washington Observatory were compared for each storm type using chi-square statistics (Table 9).

The results were mixed and suggest that, as expressed at ground level, several of the synoptic conditions are statistically similar. The generally low chi-square values for deicing cycles, wind speed and precipitation indicate that they are similar from storm to storm. Notable exceptions are between the WFS and the PCF and MFC types with respect to precipitation. Storm type is discriminated most successfully by air temperature and wind direction. Their higher chi-square values suggest that the visual classifications are independent with respect to these variables, which are often also excellent frontal passage indicators.

Overall, the MFC and CFW storm types are most similar statistically. Though this suggests the two storm types should be combined, they were left separate because the MFC type generates long and potentially more dangerous icing events.

**Storm track analysis**

Four sets of maps illustrate the sequence of events in major ice-producing storms and indicate how one synoptic weather type merges into another within a single storm. These storms produced hourly icing intensities greater than one standard deviation above the mean for most of the sequences.

*12-13 November 1983, Mount Mansfield*

This was a classic cold-front-type ice storm (PCF) (Fig. 30). Intense icing, greater than four proportional Rosemount deicing cycles per hour, began when the low-pressure center passed northeast of the mountain. Intense icing continued as the center moved north-northeast, pulling moisture inland from the North Atlantic. Cold continental air from a high to the west chilled the moisture-laden oceanic air, producing clouds and ice in the northwesterly winds. Icing rates finally decreased as the low and its moisture moved far north and the encroaching high provided stability and clearing.

*5-6 May 1984, Mount Washington*

This May sequence also began as a classic post cold front (PCF) situation but with a high-pressure cell located far to the southwest (Fig. 31). Air temperatures were near -7°C, and icing rates were greater than 120 proportional cycles per hour from 1500 GMT on 5 May to 0000 GMT the following day. Winds were northwesterly for the entire sequence. As the storm center moved north-northeast and high pressure moved northward into New England from 0900 to 1200 GMT on 6

**Table 9. Synoptic type independence by surface weather variable.**

| | MSC | | CFW | | WFS | | MFC | |
|---|---|---|---|---|---|---|---|---|
| | *Chi square* | *Sig.* | *Chi square* | *Sig.* | *Chi square* | *Sig.* | *Chi square* | *Sig.* |
| **PCF** | | | | | | | | |
| Cycles | 0.01 | 0.93 | 2.33 | 0.13 | 1.06 | 0.30 | 1.03 | 0.31 |
| Air temp | 0.02 | 0.89 | 3.23 | 0.07 | 35.51 | 0.00 | 3.42 | 0.06 |
| Precip | 0.00 | 0.99 | 0.87 | 0.35 | 13.95 | 0.00 | 0.13 | 0.72 |
| Wind speed | 2.77 | 0.10 | 1.55 | 0.21 | 4.03 | 0.04 | 10.00 | 0.00 |
| Sin WD | 1.24 | 0.27 | 0.13 | 0.71 | 43.31 | 0.00 | 2.22 | 0.14 |
| Cos WD | 0.08 | 0.78 | 16.54 | 0.00 | 27.41 | 0.00 | 10.03 | 0.00 |
| **MFC** | | | | | | | | |
| Cycles | 0.38 | 0.54 | 0.28 | 0.60 | 0.01 | 0.94 | | |
| Air temp | 1.67 | 0.20 | 0.00 | 0.99 | 17.50 | 0.00 | | |
| Precip | 0.04 | 0.84 | 1.31 | 0.25 | 10.29 | 0.00 | | |
| Wind speed | 0.23 | 0.63 | 2.24 | 0.13 | 1.47 | 0.23 | | |
| Sin WD | 3.86 | 0.05 | 0.53 | 0.47 | 28.87 | 0.00 | | |
| Cos WD | 4.74 | 0.03 | 2.63 | 0.10 | 3.86 | 0.05 | | |
| **WFS** | | | | | | | | |
| Cycles | 0.39 | 0.53 | 0.40 | 0.53 | | | | |
| Air temp | 10.57 | 0.00 | 4.73 | 0.03 | | | | |
| Precip | 4.69 | 0.03 | 3.56 | 0.06 | | | | |
| Wind speed | 0.19 | 0.66 | 0.08 | 0.77 | | | | |
| Sin WD | 8.13 | 0.00 | 18.11 | 0.00 | | | | |
| Cos WD | 7.73 | 0.01 | 0.26 | 0.61 | | | | |
| **CFW** | | | | | | | | |
| Cycles | 1.20 | 1.27 | | | | | | |
| Air temp | 1.56 | 0.21 | | | | | | |
| Precip | 0.31 | 0.58 | | | | | | |
| Wind speed | 0.36 | 0.55 | | | | | | |
| Sin WD | 1.15 | 0.28 | | | | | | |
| Cos WD | 7.56 | 0.01 | | | | | | |
| **All storm types combined** | | | | | | | | |
| Cycles | 3.32 | 0.51 | | | | | | |
| Air temp | 39.59 | 0.00 | | | | | | |
| Precip | 16.57 | 0.00 | | | | | | |
| Wind speed | 12.80 | 0.01 | | | | | | |
| Sin WD | 58.21 | 0.00 | | | | | | |
| Cos WD | 40.44 | 0.00 | | | | | | |

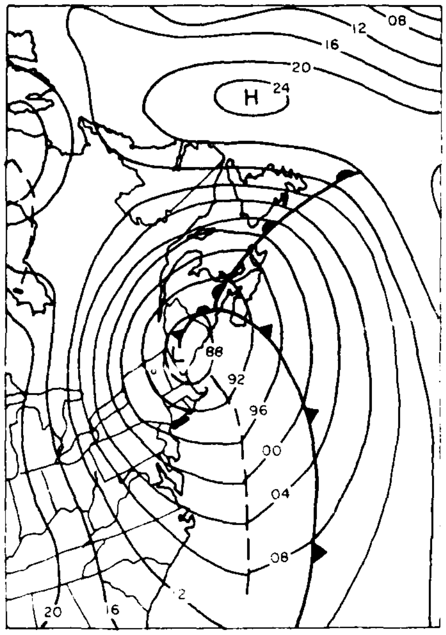
*Synoptic types:*
PCF—Post cold front with high to west.
MFC—Mountain between two cold fronts or lows.
WFS—Warm front to south.
CFW—Cold front to west, warm front usually to north.
MSC—Does not fit into other categories.

*Sfc variables:*
Cycles—Rosemount cycles for previous hour.
Air temp—Air temperature at time of map.
Precip—Precipitation for previous hour.
Wind speed—Wind speed at time of map.
Sin WD—Sine of wind direction at time of map.
Cos WD—Cosine of wind direction at time of map.

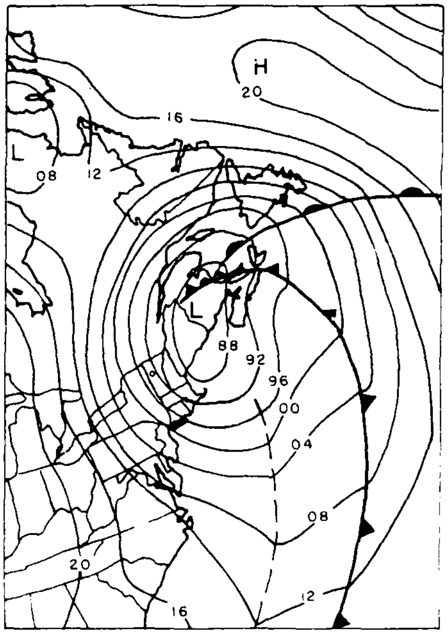
May, icing rates dropped rapidly to below 67 proportional icing cycles per hour with the loss of oceanic moisture and intrusion of the stabilizing high. In addition, a warm front following on the western side of the high advected sufficiently warm air over the mountain to stop icing. Maximum temperatures at the observatory rose to 6°C on 7 May when the warm front reached New Hampshire. Peak icing rates, from 1500 to 2100 GMT on the 5th, occurred during the highest wind speeds.

*13-14 April 1982, Mount Washington*

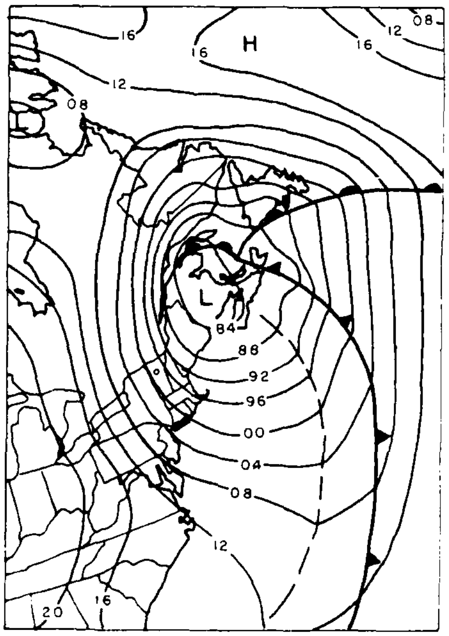
This April sequence began with Mount Washington embedded within the cloud shield of a warm front to the south (WFS) synoptic type (Fig. 32). Winds were southerly, and temperatures rose to about -2°C at 0000 GMT on 14 April. The cyclone center was located to the northwest, with an occluded front west of the mountain. From 0300 to 0600 GMT on 14 April the occlusion passed over the peak, icing intensity increased to over 360 proportional deicing cycles per hour, winds veered to the west, and temperatures decreased to -9°C. Passage of the occluded front and a trailing trough changed the synoptic situation to a post cold (occluded) front (PCF) type. After 1500 GMT on the 14th the storm center had moved far to the northeast, and the stabilizing effect of the



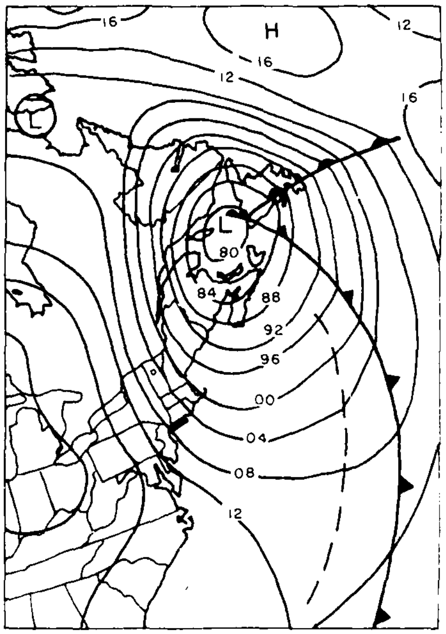

*a. Date: 12 Nov 83; Time: 0600 GMT*
*Proportional Rosemount deicing cycles/ hour: 10.*




*b. Date: 12 Nov 83; Time: 1200 GMT*
*Proportional Rosemount deicing cycles/ hour: 7.*

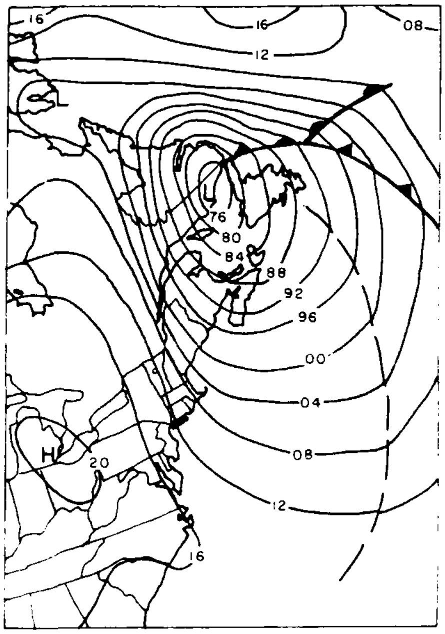



*c. Date: 12 Nov 83; Time: 1800 GMT*
*Proportional Rosemount deicing cycles/ hour: 6.*




*d. Date: 13 Nov 83; Time: 0000 GMT*
*Proportional Rosemount deicing cycles/ hour: 12.*

*Figure 30. Storm sequence of 12–13 November 1983 on Mount Mansfield, a classic post cold front (PCF) type.*




*e. Date: 13 Nov 83; Time: 0600 GMT Proportional Rosemount deicing cycles/ hour: 7.*

*Figure 30 (cont'd). Storm sequence of 12-13 November 1983 on Mount Mansfield, a classic post cold front (PCF) type.*

encroaching high began to exert its influence, reducing icing rates.

*24-26 January 1983, Mount Washington*

This is a complex sequence. Icing began with a warm front to the south (WFS) synoptic type that evolved to a post cold front (PCF) type and eventually became a multiple front and cyclone system (MFC) (though the first cold front never passed over the mountain) (Fig. 33). The icing rates were greater than 40 proportional deicing cycles per hour before 0600 GMT on the 24th, then dropped as warmer air reached the mountain, wind speeds decreased, and the low was closest and directly to the east. The air temperature rose to 0°C at 0900 GMT, winds were southerly, and icing rates dropped to three proportional deicing cycles per hour. Winds became westerly by 1200 GMT. By 1800 GMT on the 24th the low had moved about 600 km to the northeast, a cold front trailed to the south and east of Mount Washington, winds were westerly, and colder air was advected in from the west ahead of the high to the southwest. The icing rates increased during this time to well over 120 proportional deicing cycles per hour.

By 0000 to 0600 GMT on the 25th another frontal system approached from the west closely following the coastal storm and merging cloud shields. Maximum temperatures dropped to -9°C on the 25th, and the ice type changed from smooth and milky hard rime to soft rime.

Finally, icing rates dropped below 67 proportional cycles per hour after 0000 GMT on the 26th as the second cold front passed and the low had traveled over 900 km to the northeast, decreasing the moisture supply. A high-pressure cell over Canada was also beginning to influence the area by this time with its dry, stable continental polar air.

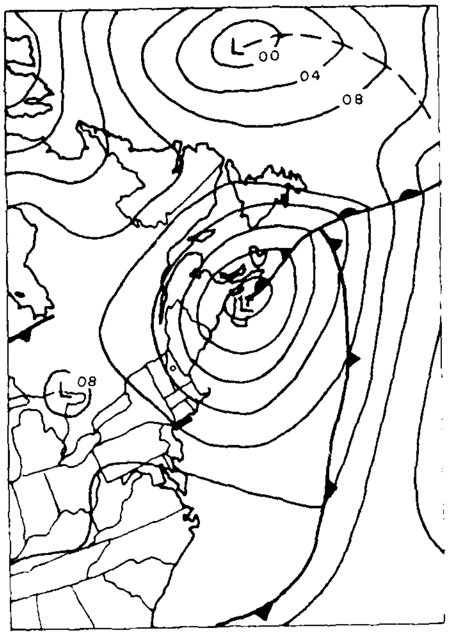
## CONCLUSIONS

Atmospheric icing is common at higher elevations in the Green Mountains and the White Mountains. The 578-m difference in elevation between Mount Mansfield and Mount Washington is certainly one cause of more frequent and intense icing on Mount Washington. Other factors enhancing Mount Washington activity may be orographic prominence and proximity to fall and early winter Atlantic coastal storms. Though correlations of icing events on the two mountains do not show a strong relationship and suggest that different factors may be enhancing icing rates on the two peaks, synoptic analyses imply otherwise and show remarkable consistency.

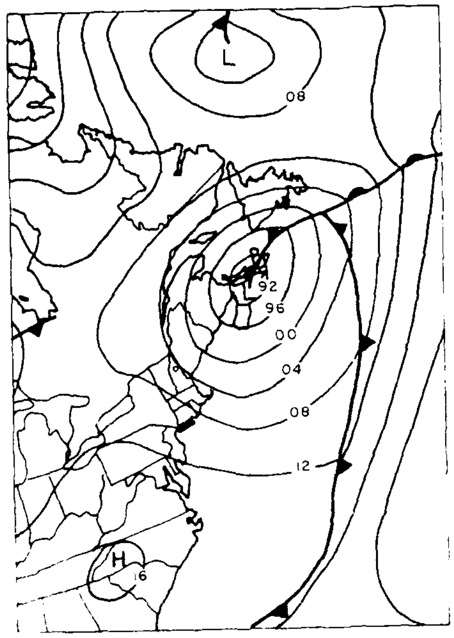
Despite the simplicity of the synoptic analyses, several patterns were identified with heavy mountain icing and are quite consistent for the two mountains. Most heavy icing occurs during or immediately after cold front passages. Icing is most intense when lows are located about 450 km directly to the east-northeast. Highs are usually located to the west at this time, usually no closer than about 450 km. Closer highs tend to suppress activity, especially because of the extreme stability found in cold, dry air plunging toward the equator on their leading southeastern sides.

## LITERATURE CITED

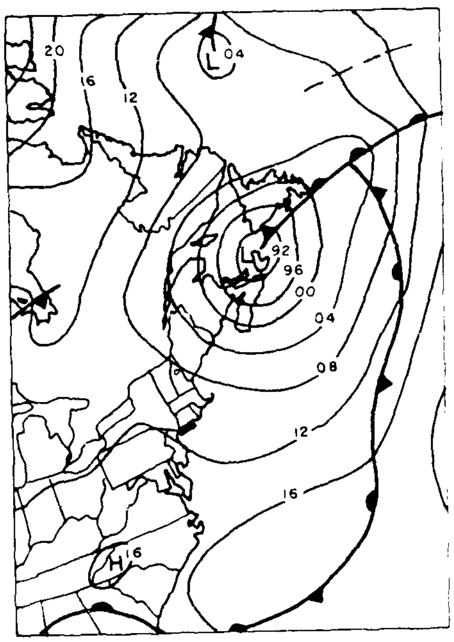
**Bennett, I.** (1959) Glaze: Its meteorology and climatology, geographical distribution, and economic effects. Natick: Quartermaster Research Engineering Command Technical Report EP-105.



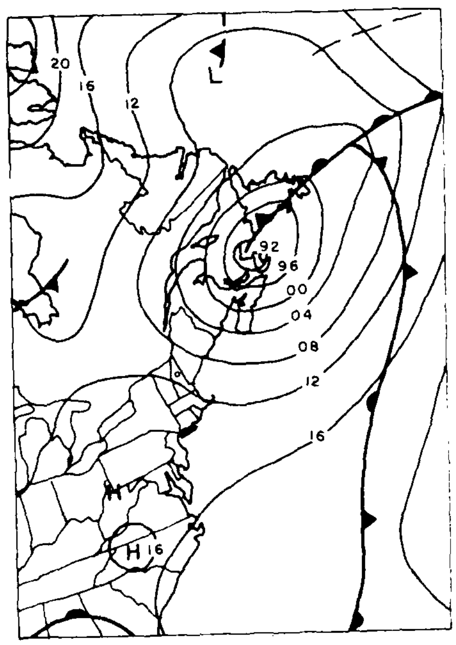

*a. Date: 5 May 84; Time: 1200 GMT*
*Proportional Rosemount deicing cycles/hr: 67*
*Temperature: -7.8°C*
*Wind direction: Northwest*
*Wind speed: 20.6 m/s*




*b. Date: 5 May 84; Time: 1500 GMT*
*Proportional Rosemount deicing cycles/hr: 360*
*Temperature: -7.8°C*
*Wind direction: Northwest*
*Wind speed: 30.8 m/s*

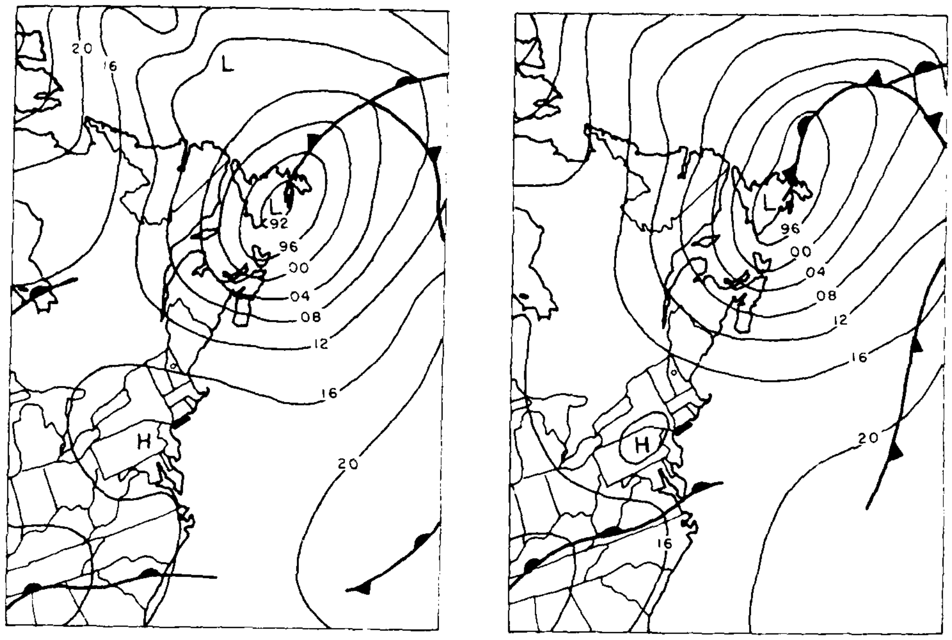



*c. Date: 5 May 84; Time: 2100 GMT*
*Proportional Rosemount deicing cycles/hr: 280*
*Temperature: -6.7°C*
*Wind direction: Northwest*
*Wind speed: 32.2 m/s*




*d. Date: 6 May 84; Time: 0000 GMT*
*Proportional Rosemount deicing cycles/hr: 189*
*Temperature: -6.2°C*
*Wind direction: Northwest*
*Wind speed: 28.6 m/s*

*Figure 31. Storm sequence of 5-6 May 1984 on Mount Washington, a classic post cold front (PCF) type.*




*e. Date: 6 May 84; Time: 0900 GMT*
*Proportional Rosemount deicing cycles/hr: 54*
*Temperature: -5.0°C*
*Wind direction: Northwest*
*Wind speed: 25.5 m/s*

*f. Date: 6 May 84; Time: 1200 GMT*
*Proportional Rosemount deicing cycles/hr: 74*
*Temperature: -3.4°C*
*Wind direction: Northwest*
*Wind speed: 27.3 m/s*

*Figure 31 (cont'd). Storm sequence of 5-6 May 1984 on Mount Washington, a classic post cold front (PCF) type.*


**Boucher, R.** (1949) A study of the meteorological factors conducive to icing on Mt. Washington. In *Contributions to the Theory of the Constitution of Clouds.* Mount Washington Observatory Research Report, Gorham, New Hampshire.

**Boucher, R.** (1950) A study of the meteorological factors conducive to icing on Mt. Washington. In *Contributions to the Theory of the Constitution of Clouds.* Mount Washington Observatory Research Report, Gorham, New Hampshire.

**Burhoe, R.** (1948) Icing on Mount Washington and the synoptic weather situation. Harvard-Mt. Washington Icing Research Report 1946-47. United States Air Force Materiel Command, Dayton, Ohio.

**Burt, F.** (1960) *The Story of Mount Washington.* Hanover: Dartmouth Publications.

**Conrad, V.** (1948) Preliminary report on statistical investigation of the Mount Washington series of icing observations. Harvard-Mt. Washington Icing Research Report 1946-47. United States Air Force Materiel Command, Dayton, Ohio.

**Gumbel, E.** (1958) *Statistics of Extremes.* New York: Columbia University Press.

**Hagerman, R.** (1971) *Mansfield: The Story of Vermont's Loftiest Mountain.* Essex Junction: Essex Publishing Co., Inc.

**Hoffer, T., T. Reale and A. Elfiqui** (1981) Icing on wind energy systems. U.S. Department of Energy, DOE/ET/23170-80/1.

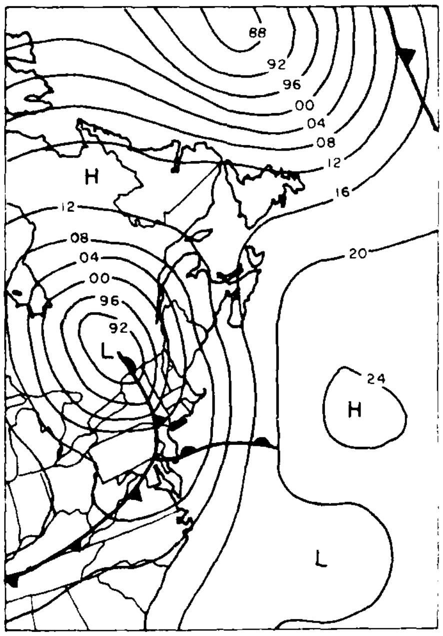
**Howe, J.** (1982) Ice research on Mt. Washington, N.H. In *Proceedings of the First International Workshop on Atmospheric Icing on Structures, Hanover, N.H.*, pp. 21-23.

**Howell, W.** (1951) A comparison of icing conditions on Mount Washington with those encountered in flight. *Transactions, American Geophysical Union,* **32**: 179-188.

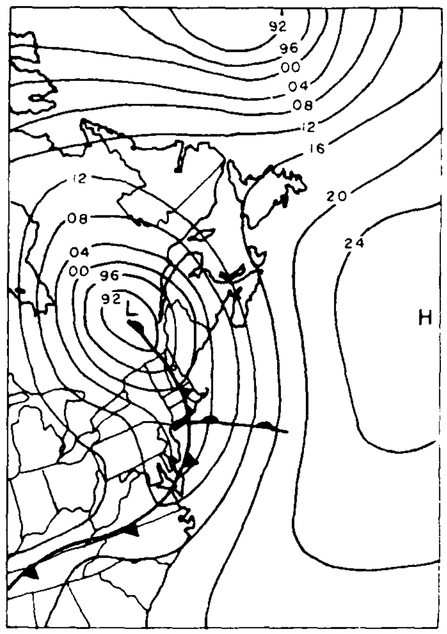
**Meeks, H.** (1986) *Vermont's Land and Resources.* Shelburne: The New England Press.

**Minsk, D.** (1980) Icing on structures. USA Cold Regions Research and Engineering Laboratory, CRREL Report 80-31.

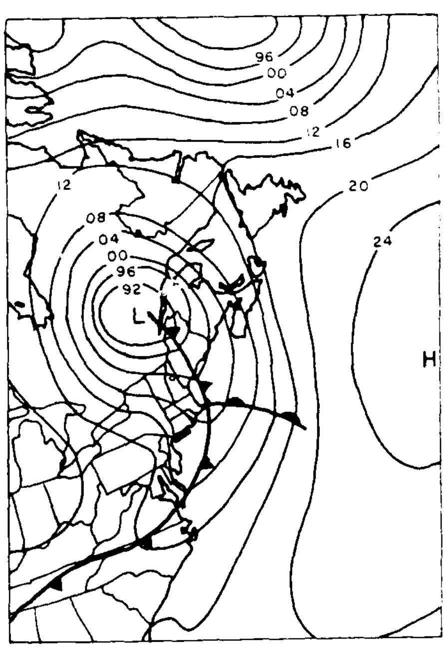
**Mount Washington Observatory** (1950) General summary. In *Contributions to the Theory of the Constitution of Clouds.* Mount Washington Observatory Research Report, Gorham, New Hampshire.



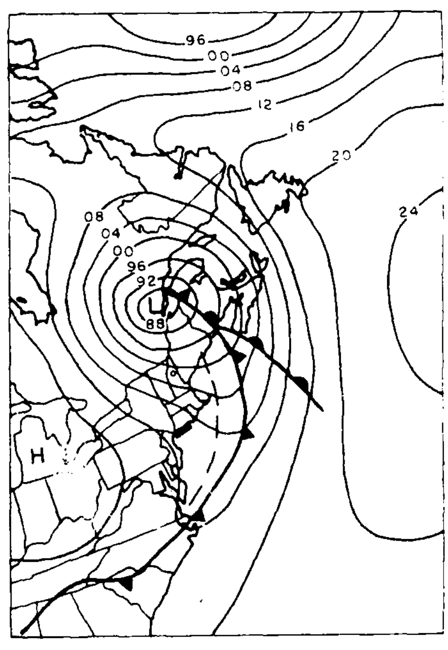

*a. Date: 13 April 84; Time: 2100 GMT*
*Proportional Rosemount deicing cycles/hr: 83*
*Temperature: -5.6°C*
*Wind direction: South*
*Wind speed: 18.3 m/s*




*b. Date: 14 April 84; Time: 0000 GMT*
*Proportional Rosemount deicing cycles/hr: 67*
*Temperature: -1.1°C*
*Wind direction: Southwest*
*Wind speed: 34.9 m/s*

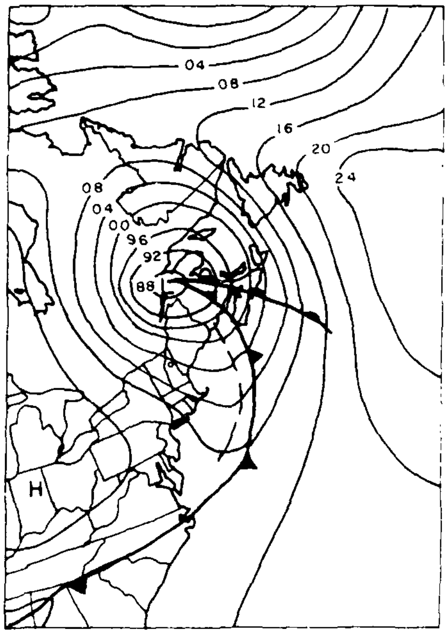



*c. Date: 14 April 84; Time: 0300 GMT*
*Proportional Rosemount deicing cycles/hr: 160*
*Temperature: -4.5°C*
*Wind direction: West*
*Wind speed: 39.7 m/s*

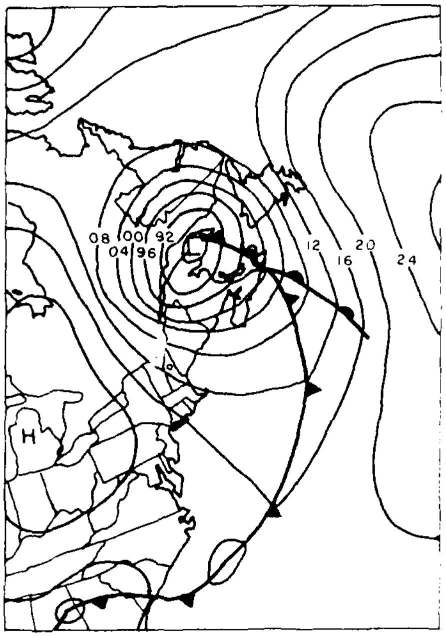



*d. Date: 14 April 84; Time: 0600 GMT*
*Proportional Rosemount deicing cycles/hr: 360*
*Temperature: -9.0°C*
*Wind direction: West*
*Wind speed: 43.4 m/s*

*Figure 32. Storm sequence of 13-14 April 1982 on Mount Washington, a warm front to south (WFS) type evolving to a post cold front (PCF) type.*




*e. Date: 14 April 84; Time: 0900 GMT*
*Proportional Rosemount deicing cycles/hr: 280*
*Temperature: -10.6°C*
*Wind direction: West*
*Wind speed: 42.5 m/s*




*f. Date: 14 April 84; Time: 1500 GMT*
*Proportional Rosemount deicing cycles/hr: 360*
*Temperature: -11.2°C*
*Wind direction: West*
*Wind speed: 38.0 m/s*

*Figure 32 (cont'd). Storm sequence of 13-14 April 1982 on Mount Washington, a warm front to south (WFS) type evolving to a post cold front (PCF) type.*

**Muller, R.** (1977) A synoptic climatology for environmental baseline analysis: New Orleans. *Journal of Applied Meteorology,* **16**: 20-33.

**Muller, R. and A. Jackson** (1985) Estimates of climate air quality potential at Shreveport, Louisiana. *Journal of Climate and Applied Meteorology,* **24**: 293-301.

**NOAA** (1982-1986) North American surface charts. National Climate Data Center, Asheville, North Carolina, U.S. Government Printing Office.

**Rosemount Engineering Co.** (1982) Model 871CB1 ice detector instruction manual. Minneapolis: Rosemount Engineering Co.

**Ryerson, C.** (1987) Rime meteorology in the Green Mountains. USA Cold Regions Research and Engineering Laboratory, CRREL Report 87-1.

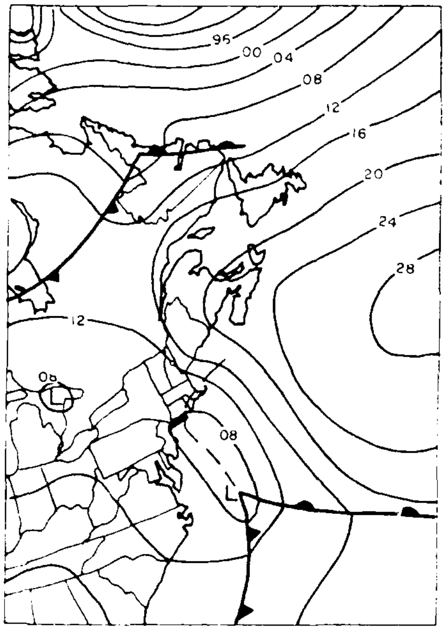
**Stewart, R. and P. King** (1987) Freezing precipitation in winter storms. *Monthly Weather Review,* **115**: 1270-1279.

**Thorp, J.** (1986) Mesoscale storm and dry period parameters from hourly precipitation data. *Atmospheric Environment,* **20**: 1683-1689.

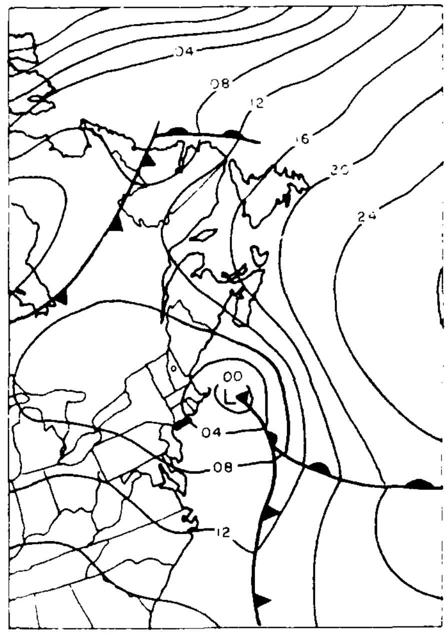
**Tucker, W. III and J. Howe** (1984) Ice detector measurements compared to meteorological parameters in natural icing conditions. In *Proceedings of Second International Workshop on Atmospheric Icing of Structures, Trondheim, Norway, June, 1984.*

**Van Diver, B.** (1987) *Roadside Geology of Vermont and New Hampshire.* Missoula: Mountain Press Publishing Company.

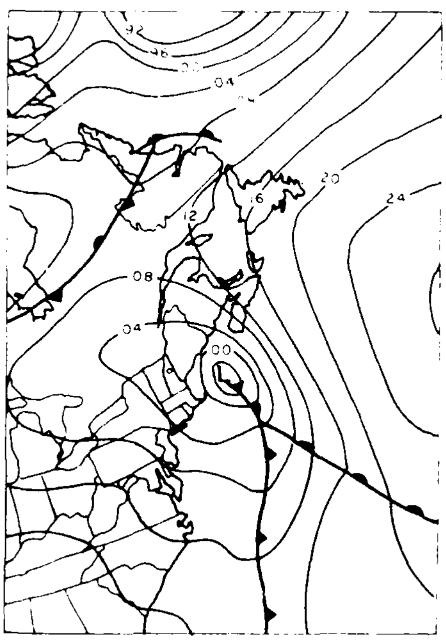
**Whipple, P.** (1948) Icing in relation to air masses and fronts. Harvard-Mt. Washington Icing Research Report 1946-47. United States Air Force Materiel Command, Dayton, Ohio.



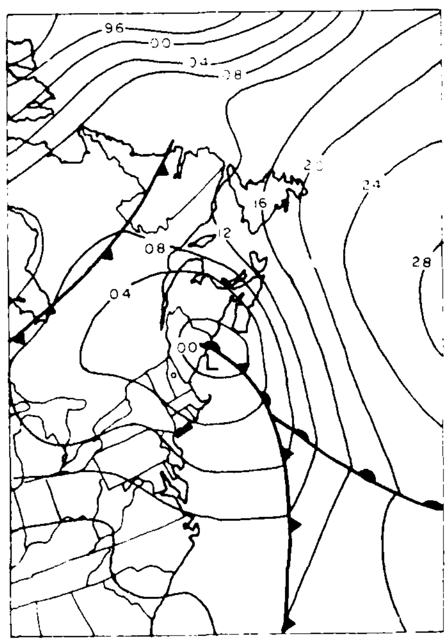
*a. Date: 24 January 83; Time: 0000 GMT*
*Proportional Rosemount deicing cycles/hr: 105*
*Temperature: -3.4°C*
*Wind direction: Southeast*
*Wind speed: 26.4 m/s*



*b. Date: 24 January 83; Time: 0600 GMT*
*Proportional Rosemount deicing cycles/hr: 13*
*Temperature: -1.1°C*
*Wind direction: South*
*Wind speed: 17.0 m/s*

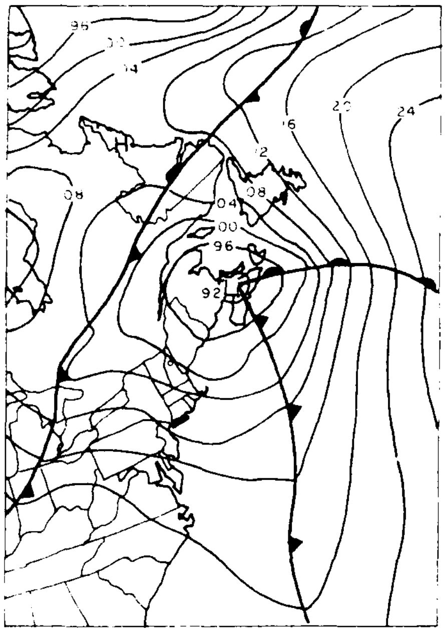


*c. Date: 24 January 83; Time: 0900 GMT*
*Proportional Rosemount deicing cycles/hr: 3*
*Temperature: -0.0°C*
*Wind direction: Southwest*
*Wind speed: 11.2 m/s*

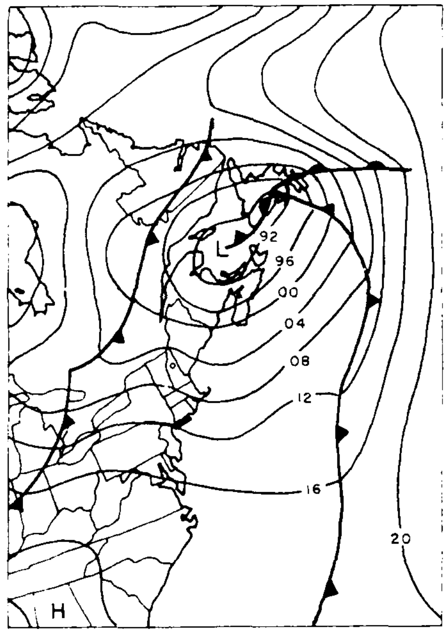


*d. Date: 24 January 83; Time: 1200 GMT*
*Proportional Rosemount deicing cycles/hr: 6*
*Temperature: -1.1°C*
*Wind direction: West*
*Wind speed: 12.5 m/s*

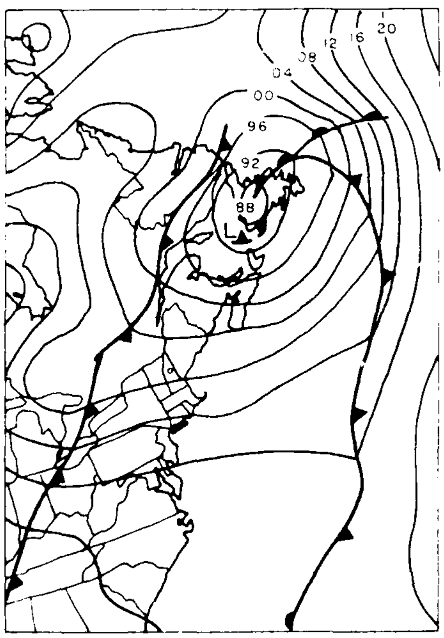
*Figure 33. Storm sequence of 24–26 January 1983 on Mount Washington, a complex multiple front or cyclone (MFC) type.*



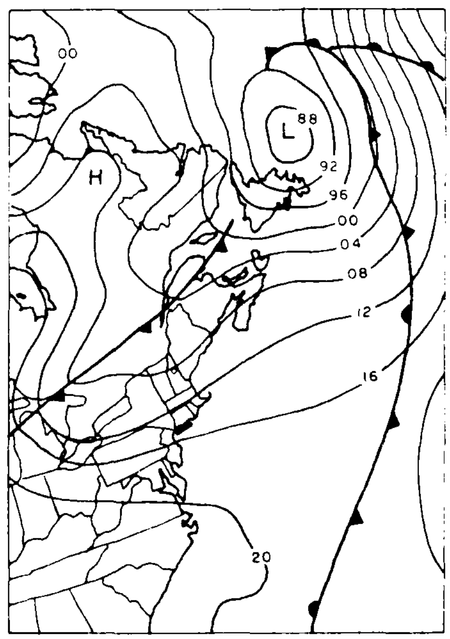

*e. Date: 24 January 83; Time: 1800 GMT*
*Proportional Rosemount deicing cycles/hr: 120*
*Temperature: -7.8°C*
*Wind direction: West*
*Wind speed: 22.4 m/s*




*f. Date: 25 January 83; Time: 0000 GMT*
*Proportional Rosemount deicing cycles/hr: 360*
*Temperature: -9.0°C*
*Wind direction: West*
*Wind speed: 29.9 m/s*

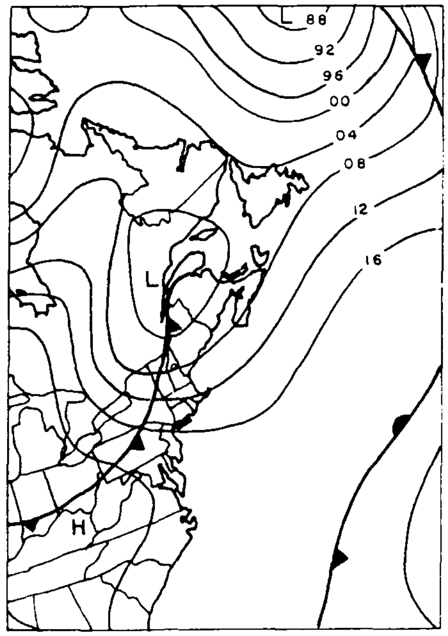



*g. Date: 25 January 83; Time: 0600 GMT*
*Proportional Rosemount deicing cycles/hr: 138*
*Temperature: -9.5°C*
*Wind direction: West*
*Wind speed: 26.4 m/s*




*h. Date: 25 January 83; Time: 1500 GMT*
*Proportional Rosemount deicing cycles/hr: 160*
*Temperature: -9.0°C*
*Wind direction: West*
*Wind speed: 20.6 m/s*

*Figure 33 (cont'd). Storm sequence of 24–26 January 1983 on Mount Washington, a complex multiple front or cyclone (MFC) type.*




*i. Date: 26 January 83; Time: 0000 GMT*
*Proportional Rosemount deicing cycles/hr: 160*
*Temperature: -11.2°C*
*Wind direction: West*
*Wind speed: 26.4 m/s*

*Figure 33 (cont'd).*



U.S. GPO: 1988-500-050/82029

A facsimile catalog card in Library of Congress MARC format is reproduced below.

Ryerson, Charles C.

New England Mountain Icing Climatology / by Charles C. Ryerson. Hanover, N.H.: U.S. Army Cold Regions Research and Engineering Laboratory; Springfield, Va.: available from National Technical Information Service, 1988.

iv, 42 p., illus.; 28 cm. (CRREL Report 88-12.)

Bibliography: p. 28.

1. Antenna icing. 2. Atmospheric icing. 3. Ice detectors. 4. Icing. 5. Mount Mansfield. 6. Mount Washington. I. United States Army. Corps of Engineers. II. Cold Regions Research and Engineering Laboratory. III. Series: CRREL Report 88-12.

**CRREL Report 88-12**
**New England Mountain Icing Climatology**
CHARLES C. RYERSON

## ERRATA

Page 9—Column 1, paragraph 2, first sentence:
"...about 4–6 times..." should read
"...about 3–5 times..."

Page 9—column 1, paragraph 2, second sentence:
"...approximately 12 proportional deicing cycles per hour..." should read
"...approximately 1–2 proportional deicing cycles per hour..."

Page 19—column 2, paragraph 2, last sentence:
"...paths of three major ice-producing storms..." should read
"...paths of four major ice-producing storms..."